SPRING RUN OFF INTO MASSACHUSETTS BAY, 1973

by

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Signature of Author...
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Certified by...
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Chairman, Departmental Committee on Graduate Students

ABSTRACT

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The depth mean salinity for the water of Massachusetts Bay from Cape Ann to Cohasset Harbor is computed at different times in the spring of 1973 to obtain the volume of fresh water in the Bay. This volume was then compared with the volume of fresh water coming into the Bay via rivers and the Deer Island sewerage treatment plant.

A good correspondence was found between the volume of fresh water in the Bay and the influx of fresh water from the spring run-off. The maximum amount of fresh water in the Bay was $2{,}450 \times 10^6$ m^3 on May 25, 1973. The major loss of fresh water from the region considered during the spring seemed to be diffusion of salt into the Bay rather than advection of fresh water out of the Bay. It was also shown that the Merrimac River accounted for about 90% of the volume of fresh water found in the Bay.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

Although as early as 1927, Bigelow did extensive studies of the Gulf of Maine,no detailed study was performed in Massachusetts Bay. Since Bigelow's study (1927) more work has been done on the whole continental shelf of the Eastern coast of North America, but these studies were primarily concerned with the current patterns for the region, Day (1958), Bumpus (1961) and Graham (1970). The only extensive salinity and temperature measurements being made was at the Boston Lightship Chase (1969).

Butman (1972) modelled a flow of fresh water into a two layer stratified ocean and compared the theoretical prediction of his model with some of the observed features of Massachusetts Bay. Beardsley and Butman (1972) summarized the known data on Massachusetts Bay and said that many of the important questions such as flushing time, could not be answered with the data then available.

The purpose of this work was to do detailed sections of the Bay to form a data base for future work and to use the data collected to determine the volume of fresh water in the Bay and compare the value so obtained with the outflow of the rivers. Many authors, Bigelow (1927), Beardsley and Butman (1972), expressed belief that the Merrimac River, which lies outside Massachusetts Bay, accounts for most of the fresh water found in the Bay. However, this had never been determined volumetrically so by determining the correspondence between the volume of fresh water in the Bay and the river discharge this question could be resolved.

The study was conducted during spring, since the vernal freshening of coastal bays is one of the major events that takes place there. Also, at this time the homogeneous state of the winter is eroded, and a thermocline and halocline is developed. Changes in salinity of the order of 3 $^{0}/00$ between the top and bottom layers are observed and strong density gradients are formed during the spring.

From Bigelow's account of the vernal freshening (1927), it was felt that in order to accurately report some of the effects taking place during the spring a complete survey of the Bay must be taken every two to three weeks.

The dates of the first five cruises were: 29-30 March; 14-15 April and 21-22 April; 5-6 May; 2-3 June and 13-14 June. A timetable of cruises every two to three weeks could not be strictly adhered to due to equipment failure and bad weather. In fact, the second cruise had to be done in two parts, part one on the 14-15 April and part two on the 21-22 April because of equipment failure. The first curise of 29-30 March and part two of the second cruise of 21-22 April were conducted on the Research Vessel W. E. Phipps, while all the other cruises were done using M.I.T.'s Research Vessel R.R. Shrock.

From the sections shown by Bigelow (1927), it was believed that a good picture of the spatial variations of the salinity and temperature in the Bay could be obtained by taking a vertical C.T.D. cast every 4-5 nautical miles (7-9 km).

In order to keep a fair amount of continuity from one cruise to another, an attempt was made to make vertical casts at the same positions as those of the first cruise. This was not always possible, however, because of the drift of the ship with currents and wind. The position of each cast is shown by the dots in Fig. 3.1 - 3.5. The position of the boat was determined by Loran B readings and radar fixes for the R. R. Shrock cruises, and by Loran C readings and radar fixes on the W. E. Phipps.

The fourth cruise of 2-3 June differed from the other cruises in that a small grid of vertical casts spaced 4 km apart was taken around two current meters located near the points labelled "C" in Fig. 3.4.

In Chapter 2 the instruments and their calibrations are discussed. The actual calibration curves are shown in Appendix B, Fig. 1 - 16. The salinity distribution on the surface and in the vertical profile is described in Chapter 3. The determination of the fresh water volume in the Bay, the description of the river flow and the comparison of the river flow with the volume of fresh water in the Bay are presented in Chapter 4. Chapter 5 is a summary of the conclusions and a discussion of some of the work left to be done.

CHAPTER 2

INSTRUMENTATION

The instruments used for this study were a continuous recording C.T.D. built at M.I.T., to obtain the vertical profile of salinity and temperature with depth, and a Bissett-Berman Model 6600 T Salinograph/ Thermograph which produces a continuous record of surface salinity and temperature. To convert the parameters conductivity, temperature and pressure measured by the C.T.D. into salinity, a subroutine, obtained from the Woods Hole Oceanographic Institute (WHOI), was used (See Appendix A). The particular subroutine used, See Appendix A, is based on data from Cox, Culkin and Riley.

The basic method for the conversion of conductivity into salinity, together with the subroutine used to do so, has been subject to question in recent years, Wooster, Lee and Dietrich (1969); Fofonoff (WHOI Report) and Haidvogel (1972). The effect the answers to these questions will have on the absolute values of salinity presented in this thesis cannot be determined at this time.

To verify the calibrations of both the C.T.D. and the Salinograph, a surface sample was taken at each station of every cruise. In addition to these surface samples, some Nansen bottle casts were made to within 6m off the bottom at certain stations on the cruises of 5-6 May and 13-14 June, 1973. These bottle samples were then analysed at WHOI, on a laboratory salinometer accurate to ± .003 ‰ in the range greater than 29.0 ‰, and to ± .01 ‰ in the range 27.0 - 29.0 ‰.

For each cruise the following information was calculated from the readings of salinities from the various instruments. S_B, the salinity reading of the bottle; S_S, the salinity reading of the Salinograph; and S_{CTD}, the salinity reading of the C.T.D. The difference between the salinity reading of the C.T.D. and that of the bottle ($S_{CTD} - S_B$) was plotted against the station number, which in effect represents time since the stations were numbered sequentially, from the start of each cruise. (See Appendix B., Fig. 1-8). Similarly, the difference between the Salinograph reading and the bottle reading ($S_S - S_B$) was plotted against the station number, (See Appendix B, Fig. 9-13).

The mean and standard deviations of these differences were calculated and the results are shown in Table 2.1 for C.T.D. and Table 2.2 for Salinograph. The following formulas were used in the computations of the mean and standard deviations for each instrument. Let $x_i = (S_I - S_B)_i$ where I represents the particular instrument, C.T.D. or Salinograph, and i is the station number. Then $\bar{x}$, the mean deviation, is given by

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

where N is the total number of stations.

The standard deviation, δ, is given by

$$\delta = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N - 1}}$$

TABLE 2.1

MEAN DEVIATIONS OF THE DIFFERENCE BETWEEN C.T.D. AND BOTTLE READINGS

Date	$\bar{x}$	δ	M.S.T.
29-30 March	.27	.028	3.3
14-15 April	.28	.026	4.0
21-22 April	.32	.026	5.9
5-6 May	.35	.040	8.5
5-6 May (bottom samples)	.32	.038	4.2
2-3 June	.45	.052	12.6
13-14 June	.54	.044	16.2
13-14 June (bottom samples)	.37	.033	4.5

$\bar{x}$ ≡ Mean Deviation ($^0/00$)

δ ≡ Standard Deviation ($^0/00$)

M.S.T. ≡ Mean in situ Temperature, (°C)

TABLE 2.2

MEAN DEVIATIONS OF THE DIFFERENCE BETWEEN SALINOGRAPH AND BOTTLE READINGS

Date	$\bar{x}$	δ	M.S.T.
29-30 March	.12	.009	3.3
14-15 April	.12	.024	4.0
21-22 April	.10	.028	5.9
5-6 May	.16	.042	8.5
13-14 June	.18	.044	16.2

$\bar{x}$ ≡ Mean Deviation ($^0/00$)

δ ≡ Standard Deviation ($^0/00$)

M.S.T. ≡ Mean in situ Temperature, (°C)

It was found that the mean deviation of the difference between the C.T.D. reading and the bottle reading increased as the survey progressed. This leads to the belief that this may be due either to temperature, since the surface waters were becoming warmer with each cruise of the survey, or it may be some drift of the calibration of the instrument with time. To settle this dilemma the deviations for each sample were plotted against their in situ temperature for two cruises. For the bottles of the cruise 29-30 March and for those of the cruise 5-6 May these plots showed what seemed to be a random variation with in situ temperature (See Appendix B, Fig. 14-15).

On the other hand, it was realized that the change in mean deviation of the C.T.D. readings from the bottle readings as the survey progressed was not a drift of the calibration with time; since the mean deviations of the samples from the bottom did not correspond with the mean deviations of the samples from the surface. This is shown in Table 2.1, for the cruise of 5-6 May and that of 13-14 June. The mean deviations for each set of samples from the surface, together with the mean deviations of each group of bottom samples were then plotted against their mean in situ temperature (M.S.T.). There seemed to be a fair correspondence between the mean deviations of the samples with their mean in situ temperature (See Appendix B, Fig. 16). Therefore, this curve (See Appendix B, Fig. 16) of mean deviations versus mean in situ temperature was used to correct the values of salinity obtained from the C.T.D.

The mean deviation of the difference of the Salinograph readings from the bottle readings, for each cruise (see Table 2.2), was used to correct the salinity readings from the Salinograph.

CHAPTER 3

SALINITY DISTRIBUTION

3.A. Surface Distribution

By the time of the first cruise, March 29-30, the effect of spring run-off was already felt in Massachusetts Bay. In some respects this was an unusually early time of the year for the spring run-off, since on March 24, 1920 no vernal freshening was observed even at the innermost stations off Massachusetts, Bigelow (1927). This year, however, water from the Merrimac had already reached the latitude of the light ship (Fig. 3.1) which is 53.8km south of the mouth of the Merrimac.

At this time the water from the rivers north of Cape Ann occupied the easternmost part of Massachusetts Bay, while the water from the rivers that emptied directly into the Bay was at the westernmost part. (Fig. 3.1). This left a pool of relatively high salinity water in the middle of the Bay, the center of the pool being at about 42°..24'..24" N and 070°..25'..42" W, i.e., near #17 as marked in Fig. 3.1.

In his report Bigelow said that the freshening of the water in Massachusetts Bay varies considerably from year to year, since it depends greatly to what extent the river run-off from north of Cape Ann hugs the coast line, Bigelow (1927). This was clearly observed by the time of the second cruise, 21-22 April (Fig. 3.2). It is observed that the tongue of fresh water from north of Cape Ann had moved approximately five nautical miles, 9.3 km, to the west and was now inside Stellwagen Bank.

No new low of salinity was observed at this time, but the pool of 31.0 - 31.6 $^0/00$ water that had been in the middle of the Bay three weeks earlier had now disappeared and the 30.4 $^0/00$ contour had moved further out from the coastline; evidence of significant amount of freshening having taking place.

It was still easy to differentiate the water from the rivers north of Cape Ann (Merrimac, Parker, Ipswich) and those that empty directly into the Bay (Charles, Mystic, Neponset, Mother Brook), by the rise and fall in salinity as one goes from west to east. (See Fig. 3.2.)

By the 5-6 May, 1973 the full effect of the spring run-off was observed, Fig. 3.3. The low salinity tongue originating north of Cape Ann had moved a further five nautical miles, 9.3km, westward, and its salinity had dropped by 2.6 $^0/00$ from 30.6 $^0/00$ to 28.0 $^0/00$. The fresh water was observed much further south than before and may even have been as far south as the Cape Cod Canal although no data was collected in this region to verify this.

The first two weeks of May generally mark the end of the freshening of the surface waters, Bigelow (1927), and this year, in that sense, seems to follow previous years. However, it would seem that there was considerably more fresh water run-off this year than in previous years, since Bigelow (1927) reports that in 1920 the surface salinity on May 4 was 29.1 $^0/00$ and was close to the minimum for the year. This year the salinity on May 5-6 was as low as 28.0 $^0/00$ over a major portion of the Bay.

At this time also, the region close to the shore of the Bay which was marked by the 30.4 $^0/00$ isohaline of 21-22 April (Fig. 3.2), was now marked by the 30.0 $^0/00$ isohaline (Fig. 3.3). The fact that the middle of the Bay, which is freshened by the Merrimac, etc., is 2 $^0/00$ less saline than the waters near the coastline, freshened by the Charles, etc., indicates how much more the freshening in Massachusetts Bay depends on the rivers north of Cape Ann rather than those that empty into the Bay directly.

. Following the same trend as was observed by Bigelow (1927) the Bay began to "salt up" soon after this date. By the 2-3 of June the low salinity tongue of 28.0 $^0/00$ water in the middle of the Bay had increased to about 28.8 $^0/00$, with only a small tongue of 28.6 $^0/00$ extending to the tip of Stellwagen Bank,(See Fig. 3.4).

On the other hand, the water nearest the coastline showed further decrease and there was no 30.0 $^0/00$ water in the Bay at this time. This, however, does not necessarily mean that the Charles, Neponset and Mystic have continued discharging at a relatively high rate while the Merrimac and others north of Cape Ann have started to diminish in their outflow. It could be due to the Merrimac's water from the middle of the Bay having had time to diffuse horizontally and thus lowered the salinity of the water as we go west from the middle of the Bay. Which of these two factors is the more important will be considered later in the thesis, when a look is taken at the river outflow for the corresponding months.

By the 13-14 June 1973, the salting effect was being felt all over the Bay, and thus marks the end of the spring run-off. The lowest salinity water is still in the middle of the Bay with the salinity increasing to both the East and the West (Fig. 3.5). At this time pockets of high salinity water amongst the low salinity water is observed; this feature is not unique to Massachusetts Bay but seems to be a characteristic of the Gulf of Maine, Bigelow (1927).

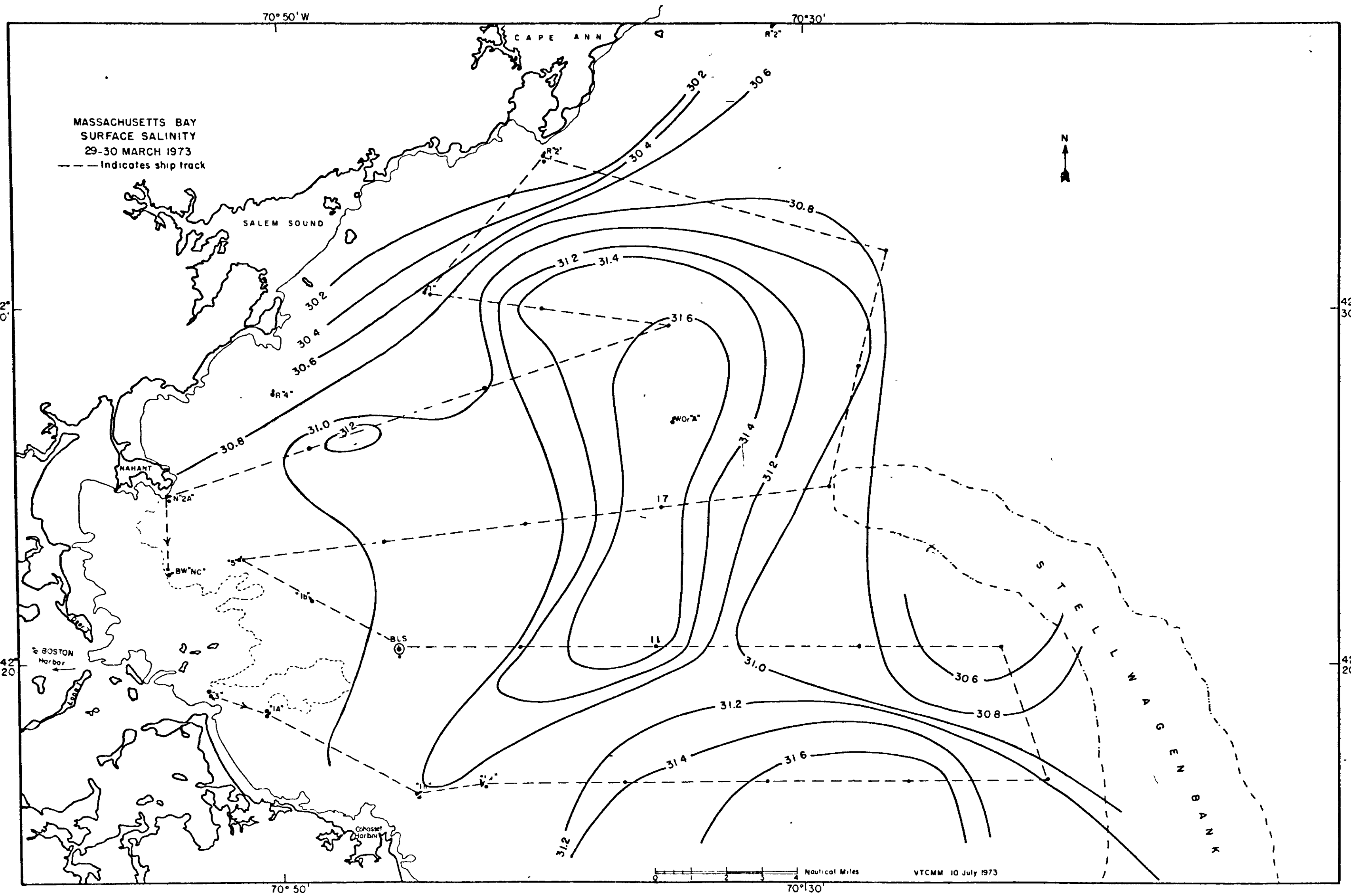

MASSACHUSETTS BAY
SURFACE SALINITY
29-30 MARCH 1973
Indicates ship track
CAPE ANN
SALEM SOUND
NAHANT
To BOSTON Harbor
Cohasset Harbor
STELLWAGEN BANK
70° 50' W
70°30'
70° 50'
70°30'
42° 30'
42° 30' N
42° 20'
42° 20'
N
30.2
30.4
30.6
30.8
31.0
31.2
31.4
31.6
Nautical Miles
VTCMM 10 July 1973

Figure 3.1

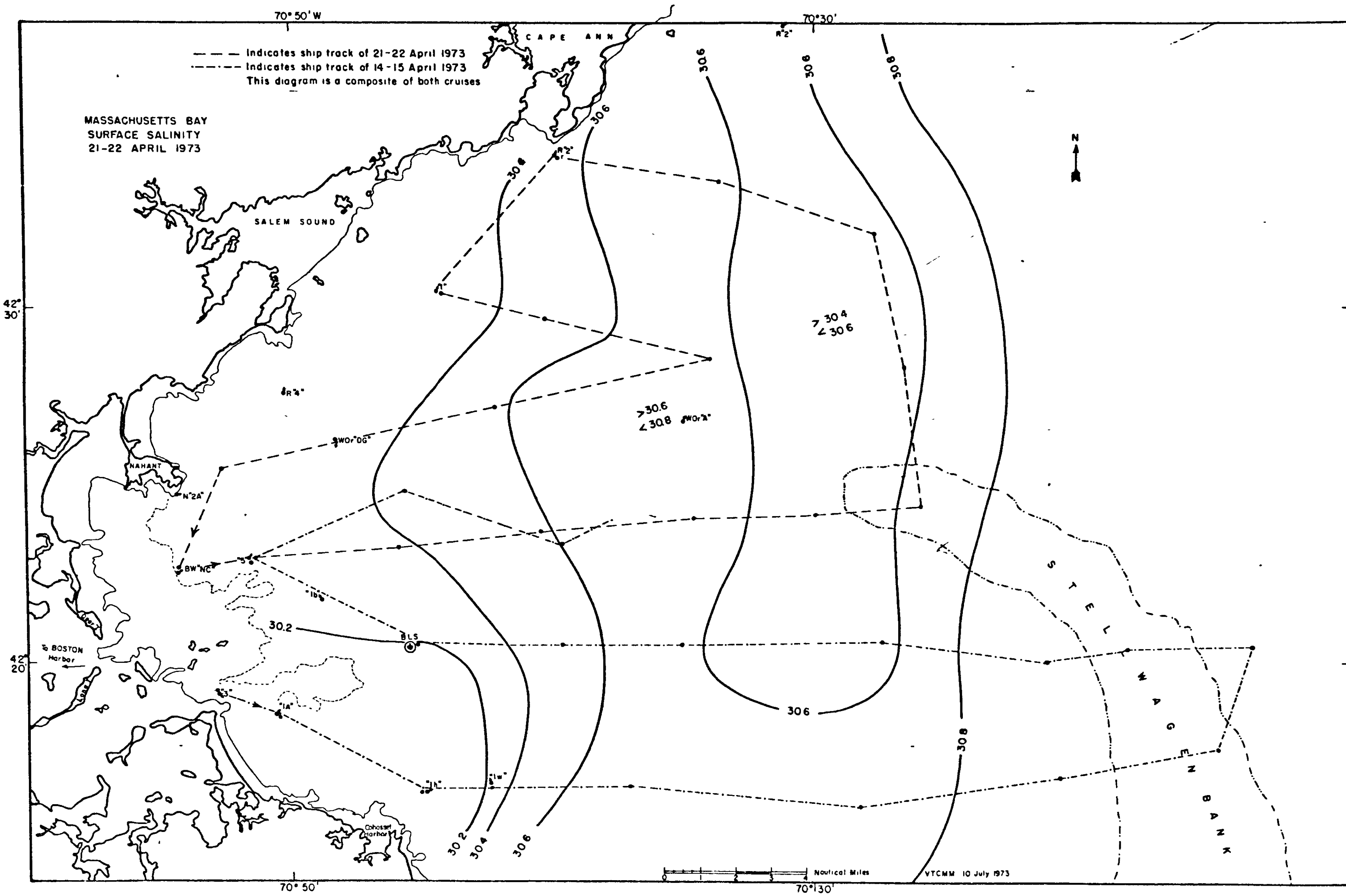

MASSACHUSETTS BAY
SURFACE SALINITY
21-22 APRIL 1973
Indicates ship track of 21-22 April 1973
Indicates ship track of 14-15 April 1973
This diagram is a composite of both cruises
70° 50' W
70°30'
CAPE ANN
SALEM SOUND
NAHANT
To BOSTON Harbor
Cohasset Harbor
STELLWAGEN BANK
42° 30'
42° 30' N
42° 20'
70° 50'
70°30'
BLS
30.2
30.4
30.6
30.8
>30.4
<30.6
>30.6
<30.8
Nautical Miles
VTCMM 10 July 1973

Figure 3.2

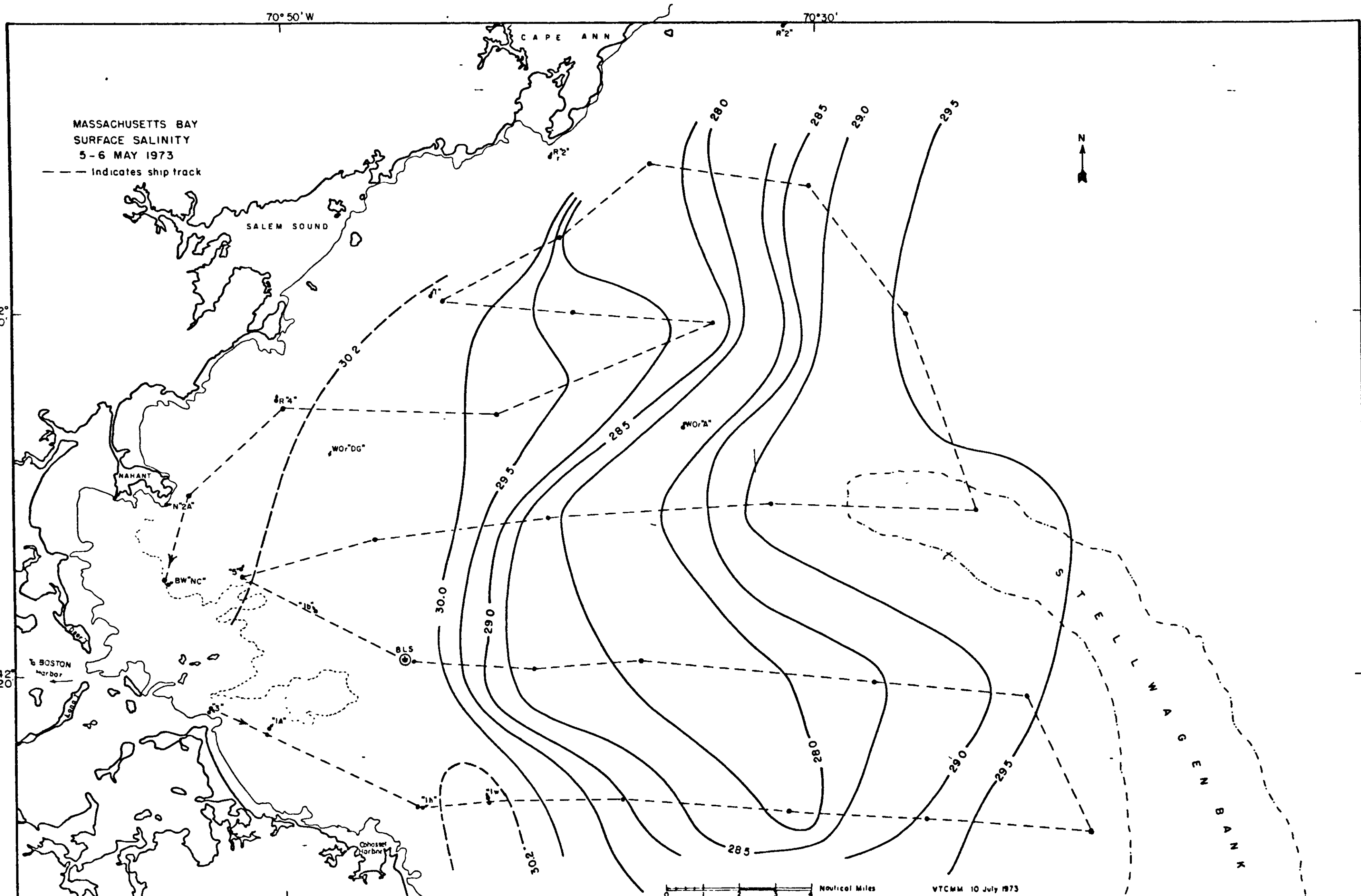

MASSACHUSETTS BAY
SURFACE SALINITY
5-6 MAY 1973
Indicates ship track
70° 50' W
70°30'
CAPE ANN
SALEM SOUND
NAHANT
To BOSTON Harbor
Cohasset Harbor
STELLWAGEN BANK
42° 30'
42° 30' N
42° 20'
70° 50'
70° 30'
Nautical Miles
VTCMM 10 July 1973
N
28.0
28.5
29.0
29.5
30.0
30.2

Figure 3.3

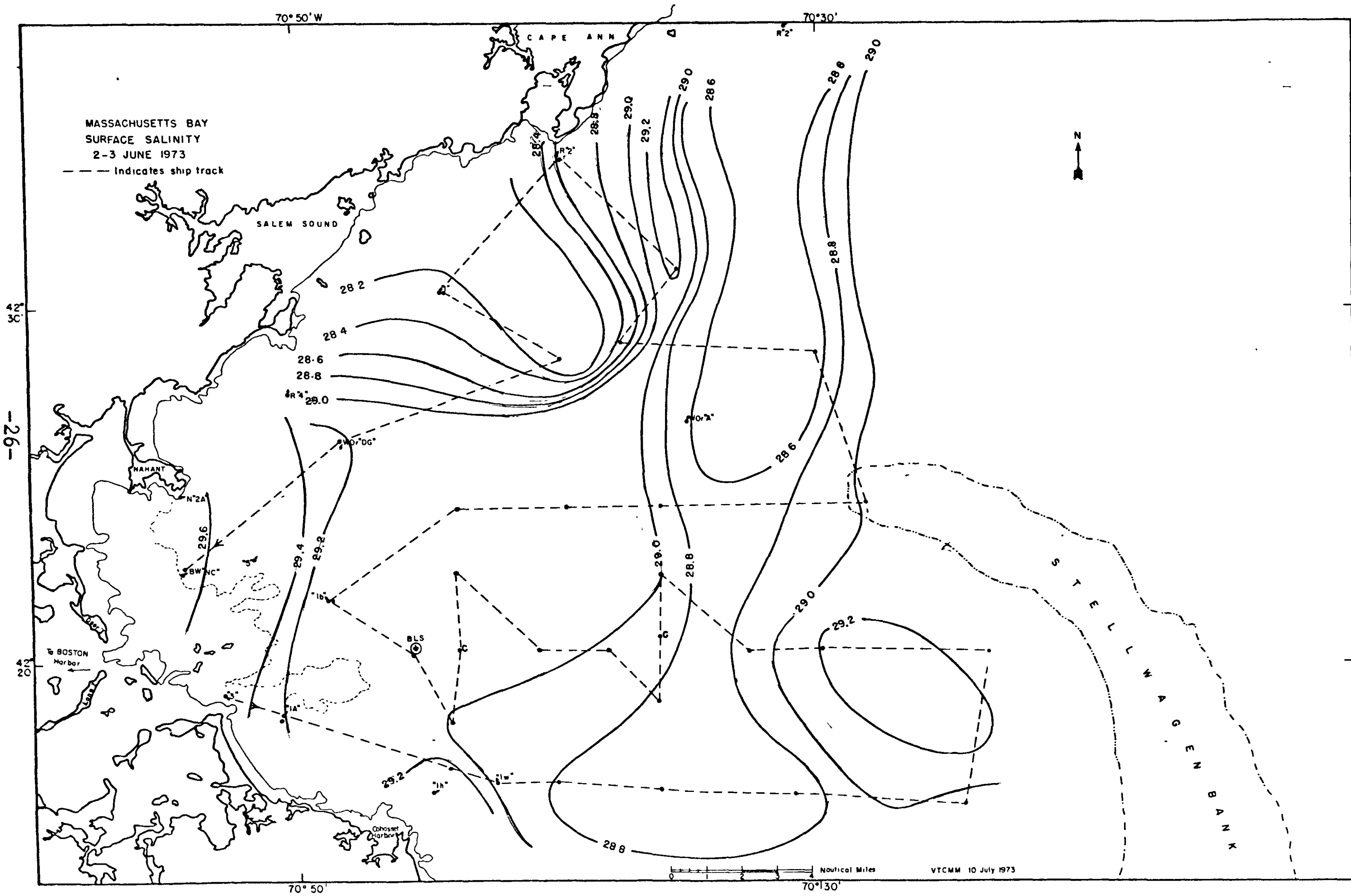
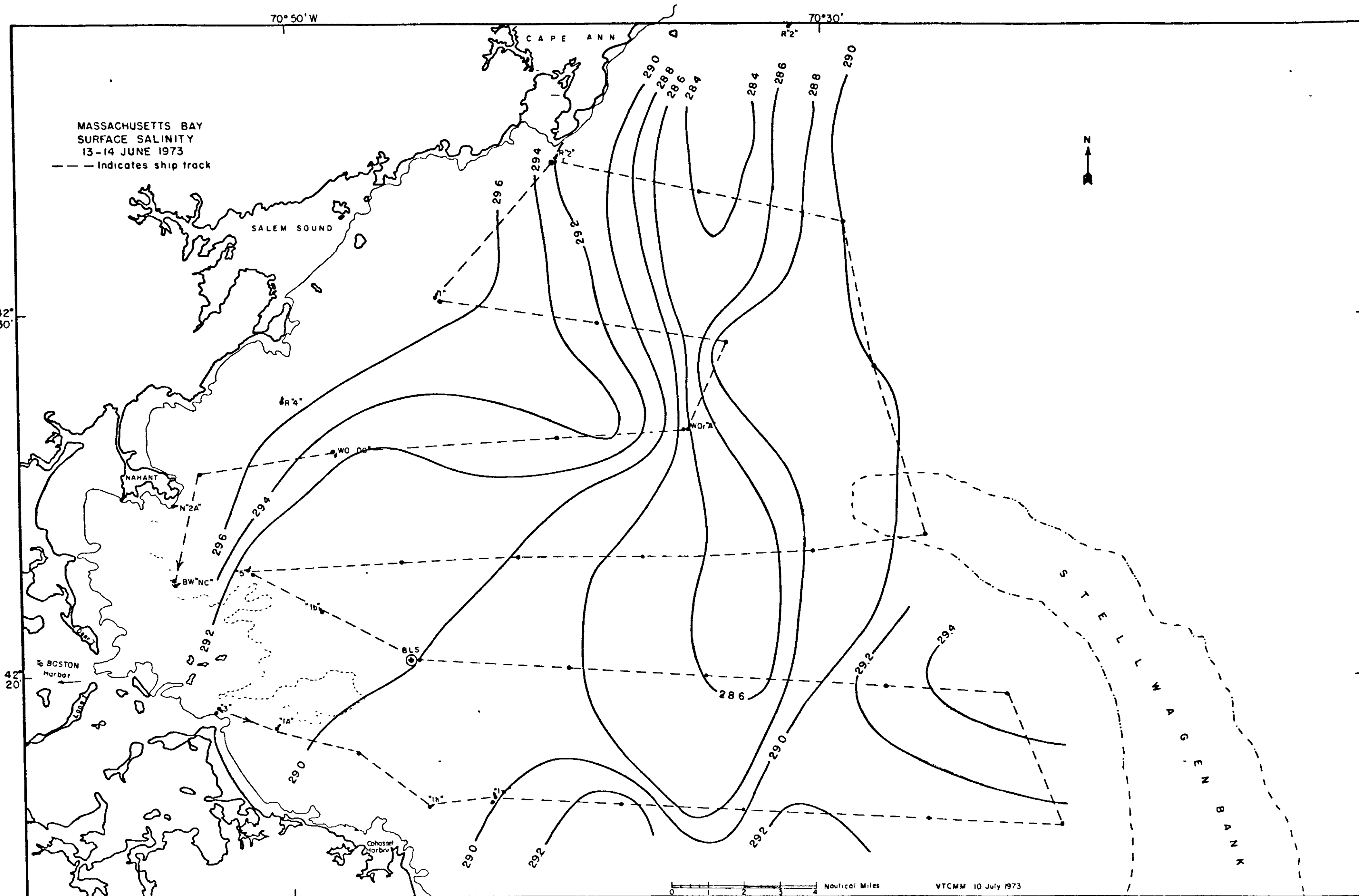

MASSACHUSETTS BAY
SURFACE SALINITY
2-3 JUNE 1973
Indicates ship track
70° 50'W
70°30'
CAPE ANN
SALEM SOUND
NAHANT
To BOSTON Harbor
Cohasset Harbor
STELLWAGEN BANK
42° 30'
42° 30'N
42° 20'
42° 20'
70° 50'
70°30'
28.2
28.4
28.6
28.8
29.0
29.2
29.4
29.6
BLS
Nautical Miles
VTCMM 10 July 1973

Figure 3.4



MASSACHUSETTS BAY
SURFACE SALINITY
13-14 JUNE 1973
— — Indicates ship track
70° 50' W
70°30'
CAPE ANN
SALEM SOUND
NAHANT
To BOSTON Harbor
Cohasset Harbor
STELLWAGEN BANK
42° 30'
42° 30' N
42° 20'
70° 50'
70°30'
Nautical Miles
VTCMM 10 July 1973
N
BLS
290
288
286
284
292
294
296

Figure 3.5

3.B. Vertical Distribution

The effect of the spring run-off in the vertical profile is seen to be quite deep even as early as 29-30 March 1973. In Section A, Fig. 3.6, the freshening due to the Merrimac, Parker and Ipswich is observed as a small bowl of low salinity water at station 9, but with its influence being felt almost to station 11 about 18 km to the West, and to a depth of 25m in the region of station 10.

The waters from the Charles, Neponset and Mystic are seen in Fig. 3.6 in the upper left hand corner as a much smaller freshening with lower salinity than the bottom water but almost 1 $^{0}/00$ higher than that of the Merrimac. These two masses of fresh water are separated by a small ridge of high salinity water, left over from winter, centered about station 11.

The Merrimac's water is not fully observed in Section B of the 29-30 March, Fig. 3.7, since this section was drawn just to the West of the flow of the Merrimac, Fig. 3.1. However, the freshening around the coastline is easily observible and the 31.4 $^{0}/00$ isohaline is 25m deep at station 22.

By the 14-15 April the Merrimac's water was observed as a bowl of 30.6 $^{0}/00$ water centered at station 13, see Fig. 3.9, with a depth of about 25m. The fact that this low salinity water is observed so far south and so deep is evidence of the fresh water volume of the rivers north of Cape Ann and also of the mixing in the water column.

Once more the Merrimac's water is separated from the Charles etc. by a ridge of high salinity water. However, by this time, 14-15 April, the ridge had dropped in salinity from approximately 31.8 $^{0}/00$ at the surface to approximately 30.8 $^{0}/00$ at the surface.

The Merrimac water is again evident to about 20m, at Section B 15km to the North of Section A (Fig. 3.10) on the 21-22 April. The near-shore water shows up much more strongly in this section than in the previous ones, and is probably due to the cumulative effect of the spring run-off.

By the 5-6 May, the full effect of the vernal freshening was being felt in the Bay. At Section A, (Fig. 3.12) there is a small bowl of 28.0 $^{0}/00$ water encompassing stations 11 and 12; this water represents near the lowest salinity water the Bay would contain for this spring. At this time, the halocline layer is well developed and is between 5-10m. This contrasts decidedly with Fig. 3.9, Section A, 14-15 April, in which no halocline is observed.

Section B, 5-6 May, Fig. 3.13, shows the same general characteristics as described for Section A, 5-6 May. A good indication of how much freshening had taken place in the two weeks between the cruises of 21-22 April and that of 5-6 May, is given by the 30.6 $^{0}/00$ isohaline. In Fig. 3.10 for 21-22 April, the 30.6 $^{0}/00$ isohaline is only shown as a small intrusion from the West with a maximum depth of 7m. In Fig. 3.13 for 5-6 May, on the other hand, the 30.6 $^{0}/00$ contour stretches across the whole Bay at an average depth of 12m.

At the time of the next cruise, 2-3 June, the surface waters had started to get more saline. However, the bottom waters were still getting fresher, which corresponds with Bigelow (1927), who observed that the bottom waters reach their lowest salinity after the surface waters had started to get more saline. A comparison of Figures 3.12 and 3.15, Section A for 5-6 May and 2-3 June, respectively, show that while there was still regions of 32.2 $^0/00$ water near the bottom at 5-6 May, there was none on the 2-3 June. Also, by the 2-3 June the 32.0 $^0/00$ isohaline had dropped by about 10m.

Similar effects are observed at Section B, 2-3 June, Fig. 3.16, as for Section A. In this case, though, not only had the 32.2 $^0/00$ water disappeared but there was no 32.0 $^0/00$ water, the most saline water being 31.8 $^0/00$. The halocline layer is easily observed at between 7-15m at the eastern side of the Bay.

By the last cruise of 13-14 June, the surface layer had not become appreciably more saline than that which existed on the 2-3 June. However, at Section A, Fig. 3.18, the bottom waters seemed to have gotten more saline. This is seen by the 32.0 $^0/00$ isohaline having moved about 5m upward.

At Section B, Fig. 3.19, however, the bottom waters continued becoming fresher and the 31.8 $^0/00$ isohaline had moved downward by approximately 20m in the 11 days between the times of the last two cruises. This difference between Section A and Section B is not strange since Section B is located closer to the rivers that contribute the most to the vernal freshening. This would mean that Section B would experience the vernal freshening at an earlier date than Section A, and also experience the salting of the Bay at a later date than would be experienced at Section A.

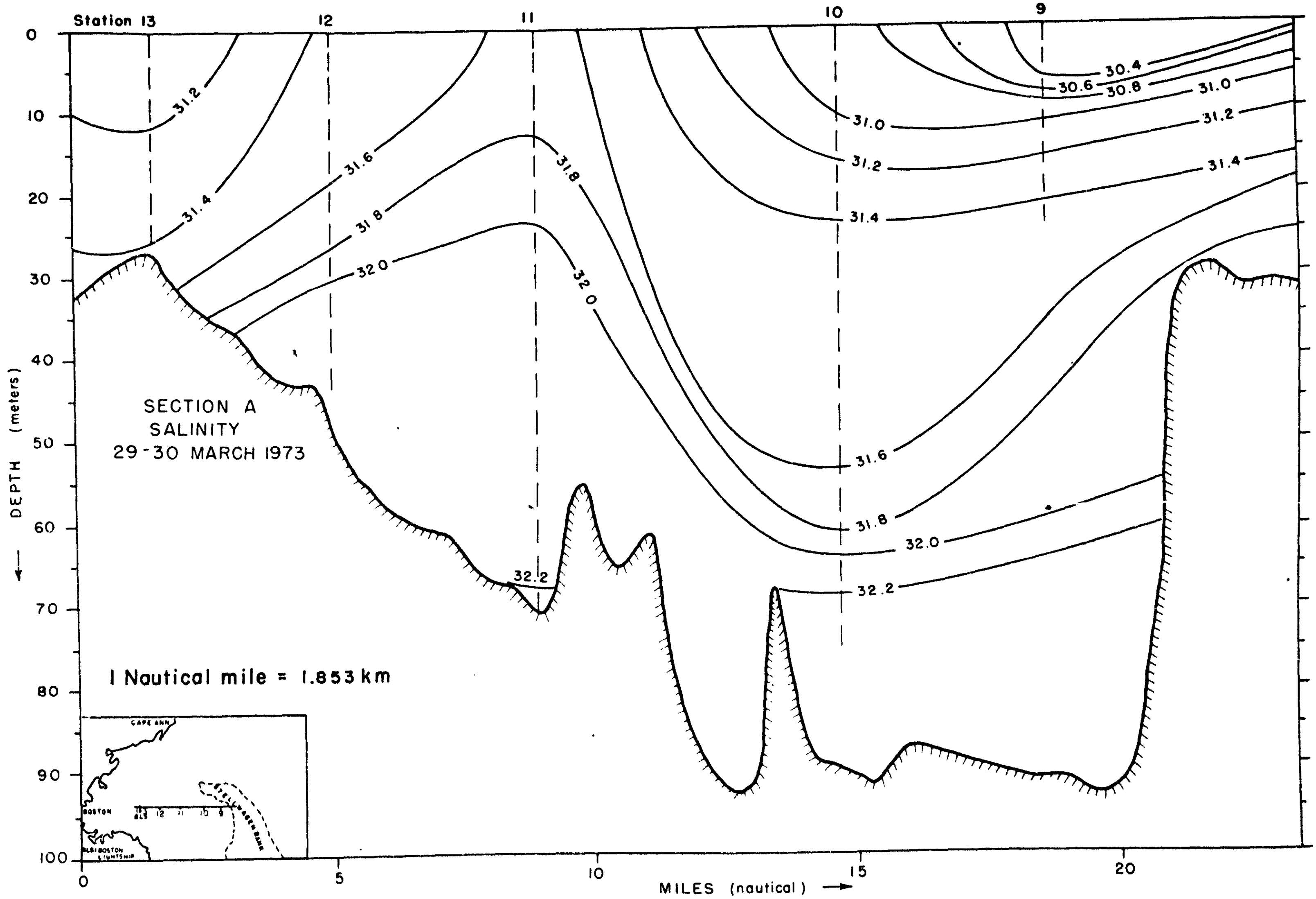

Station 13
12
11
10
9
SECTION A
SALINITY
29-30 MARCH 1973
I Nautical mile = 1.853 km
DEPTH (meters)
MILES (nautical)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
30.4
30.6
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2

Figure 3.6

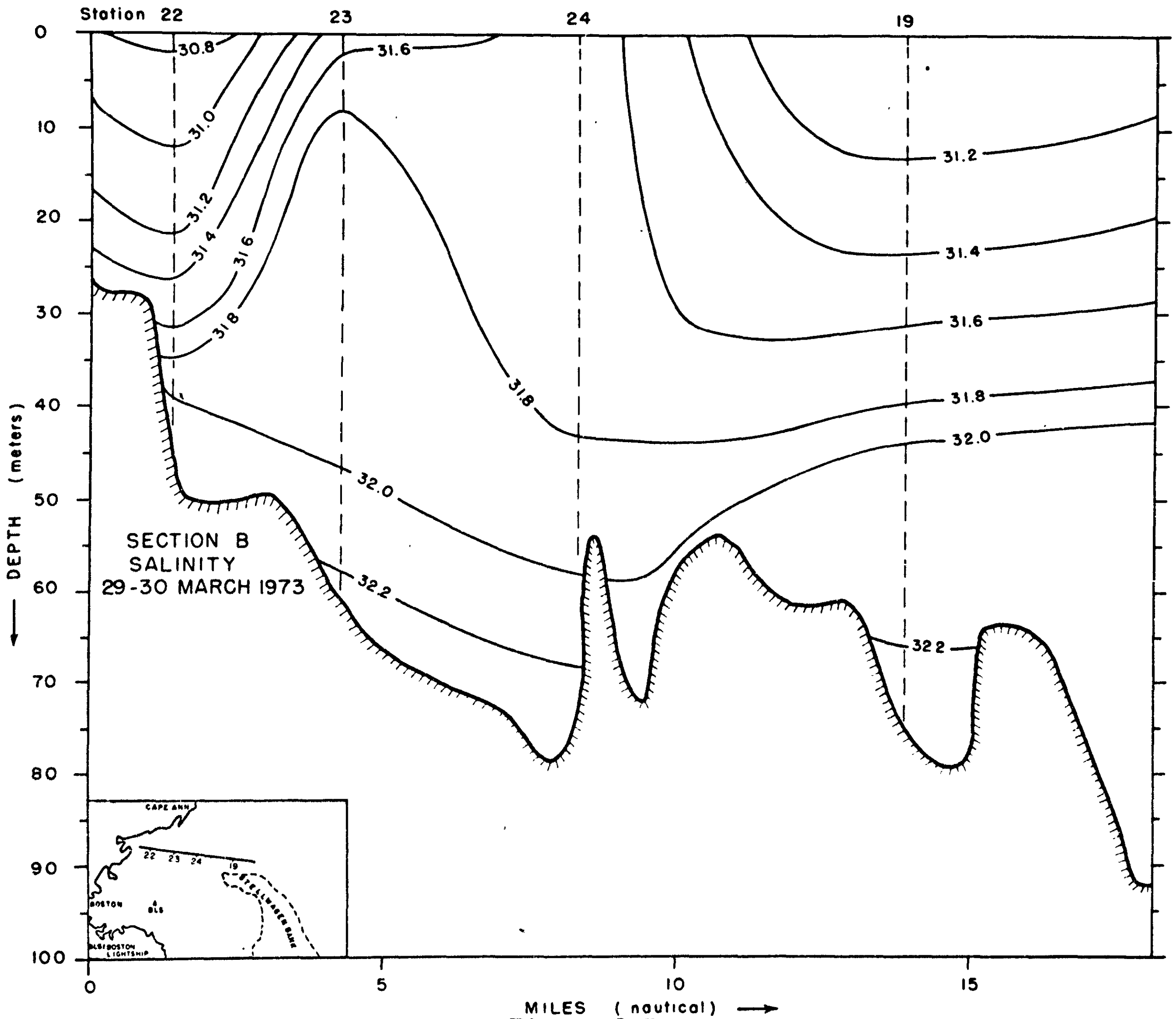

Station 22
23
24
19
SECTION B
SALINITY
29-30 MARCH 1973
DEPTH (meters)
MILES (nautical)
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
0
10
20
30
40
50
60
70
80
90
100
5
15
CAPE ANN
BOSTON
BOSTON LIGHTSHIP

Figure 3.7

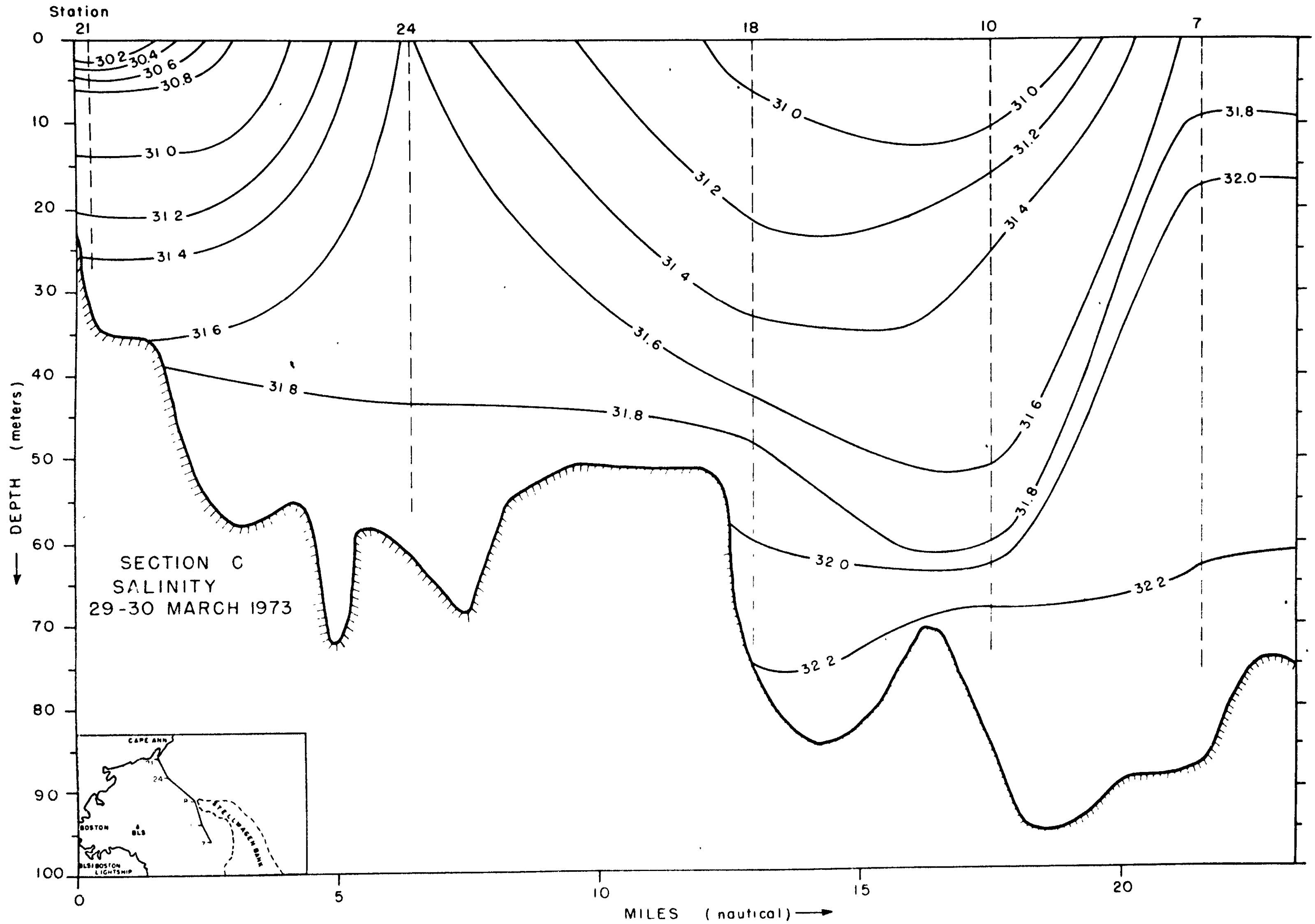

Station
21
24
18
10
7
DEPTH (meters)
MILES (nautical)
SECTION C
SALINITY
29-30 MARCH 1973
30.2
30.4
30.6
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
CAPE ANN
BOSTON
BLS
STELLWAGEN BANK
BLS: BOSTON LIGHTSHIP

Figure 3.8

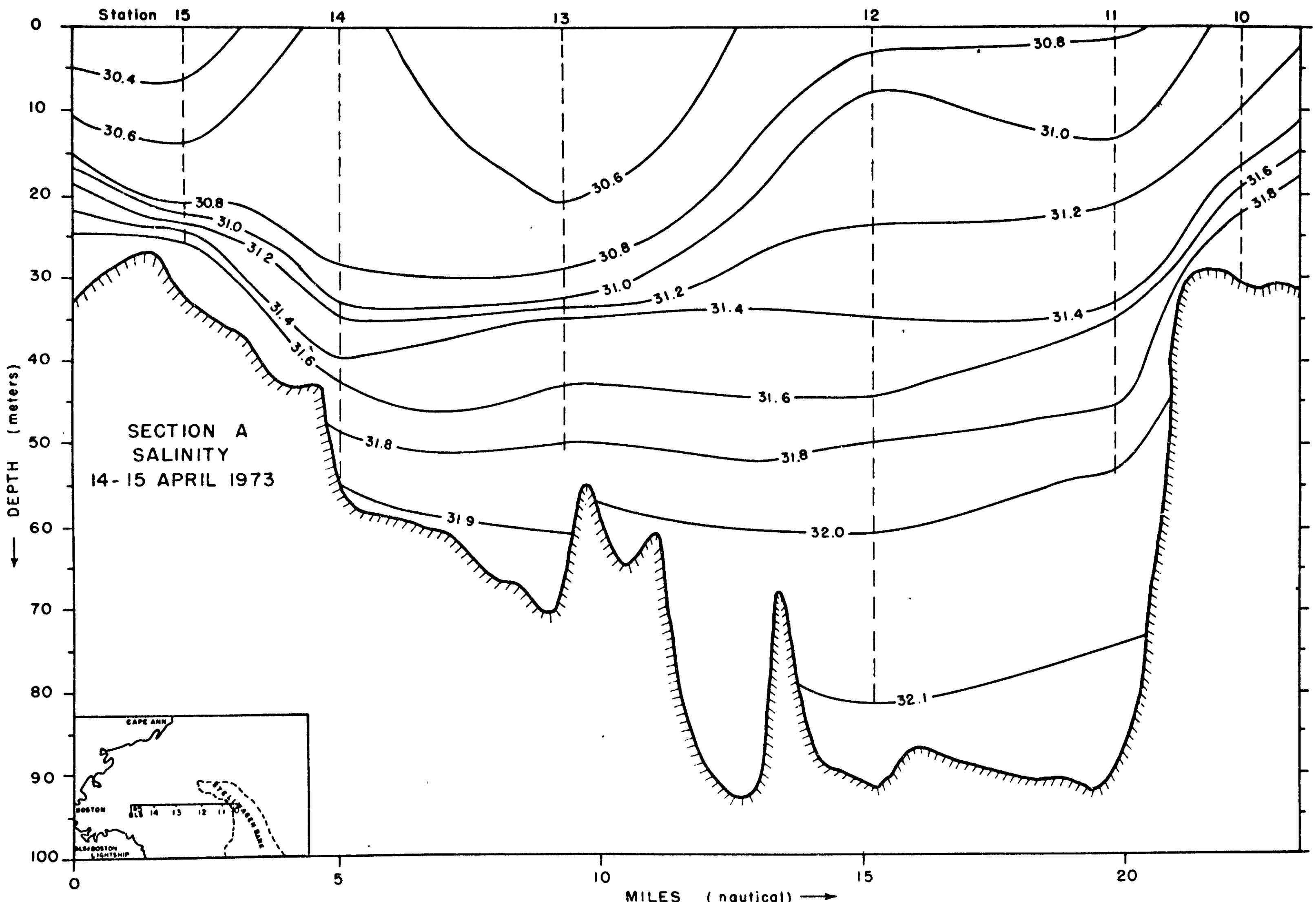

Station 15 14 13 12 11 10
SECTION A
SALINITY
14-15 APRIL 1973
DEPTH (meters)
MILES (nautical)
30.4
30.6
30.8
31.0
31.2
31.4
31.6
31.8
31.9
32.0
32.1
0 10 20 30 40 50 60 70 80 90 100
0 5 10 15 20
CAPE ANN
BOSTON
BOSTON LIGHTSHIP

Figure 3.9

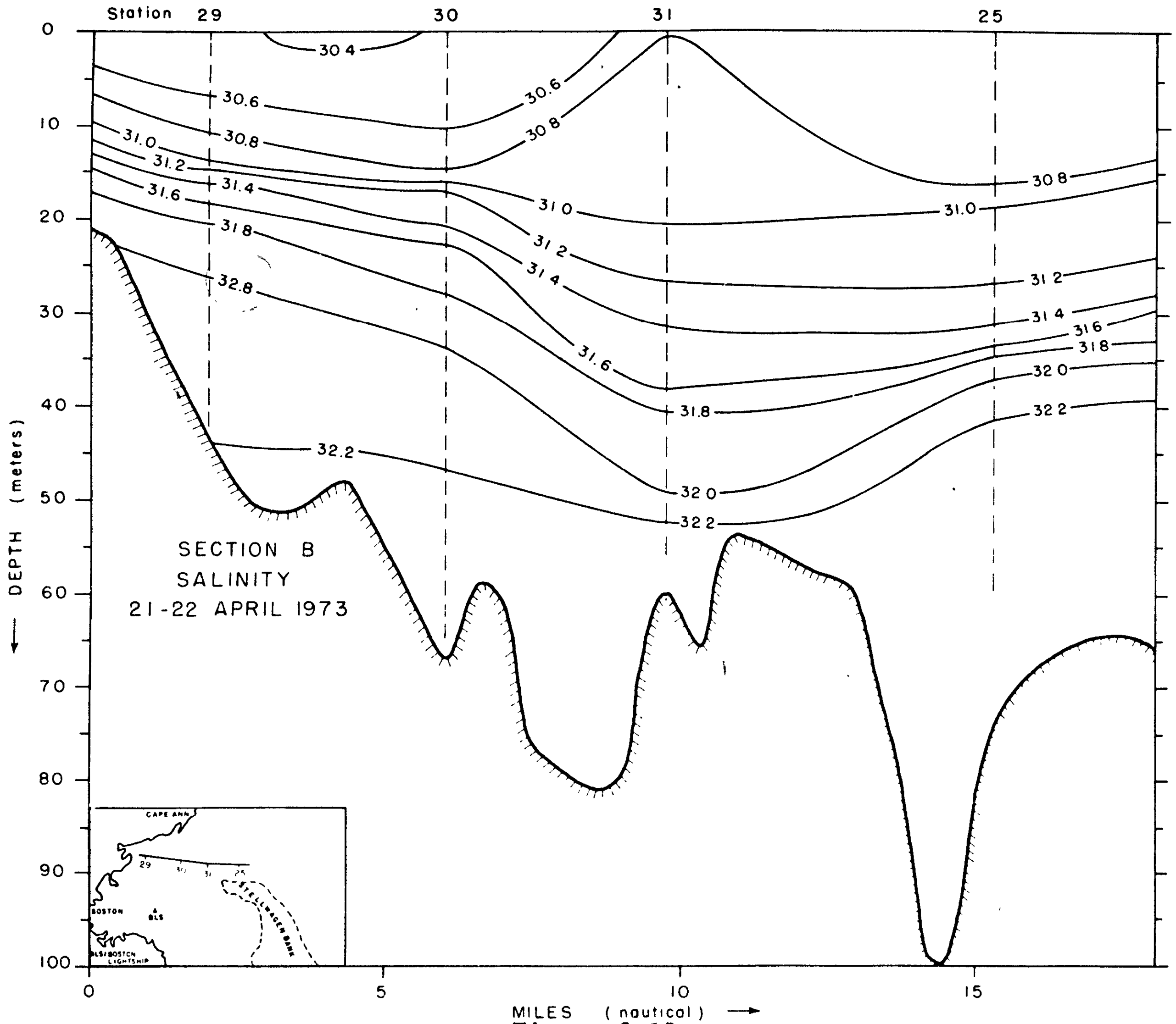

Station 29 30 31 25
SECTION B
SALINITY
21-22 APRIL 1973
DEPTH (meters)
MILES (nautical)
30.4
30.6
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
CAPE ANN
BOSTON
STELLWAGEN BANK

Figure 3.10

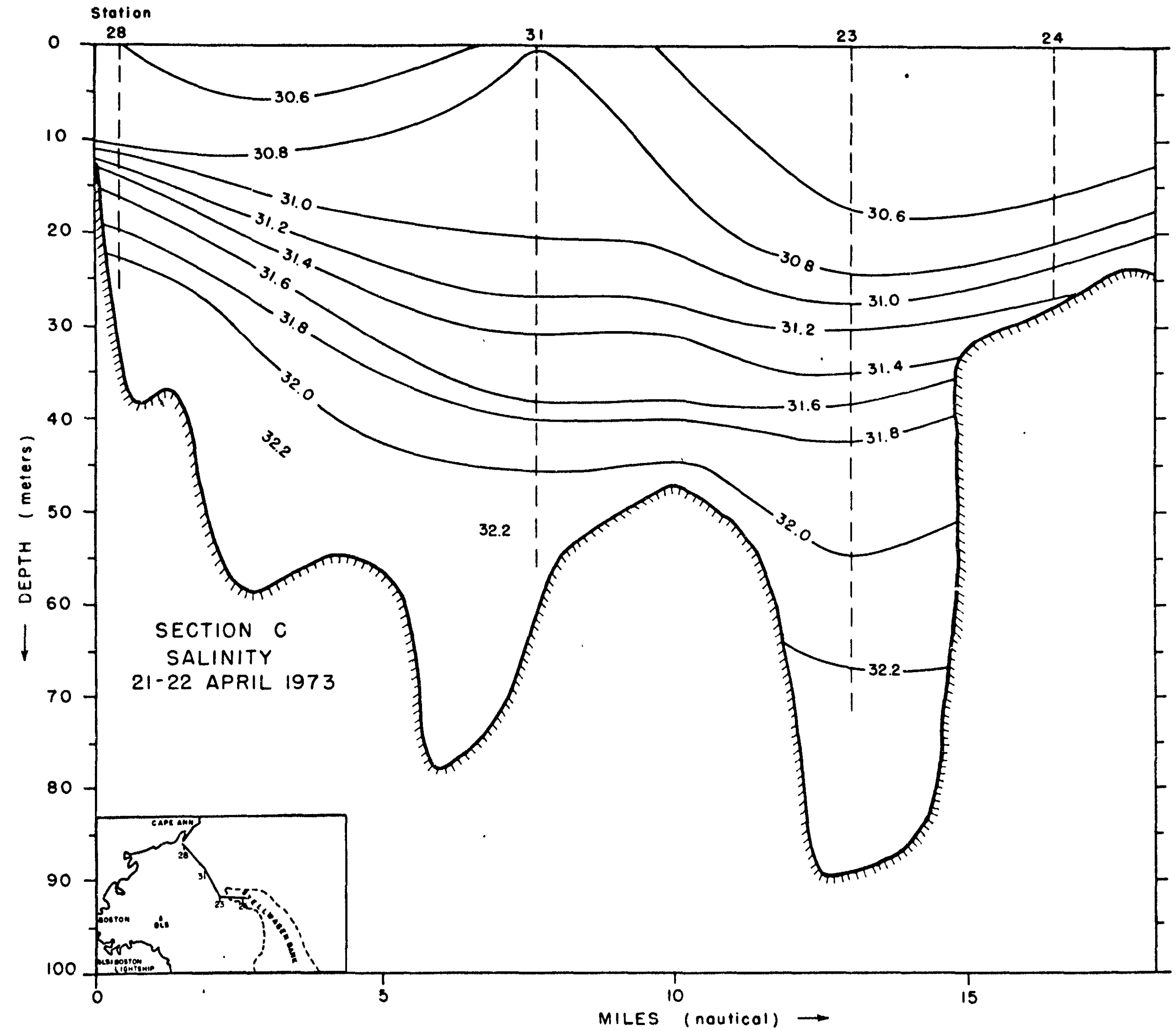
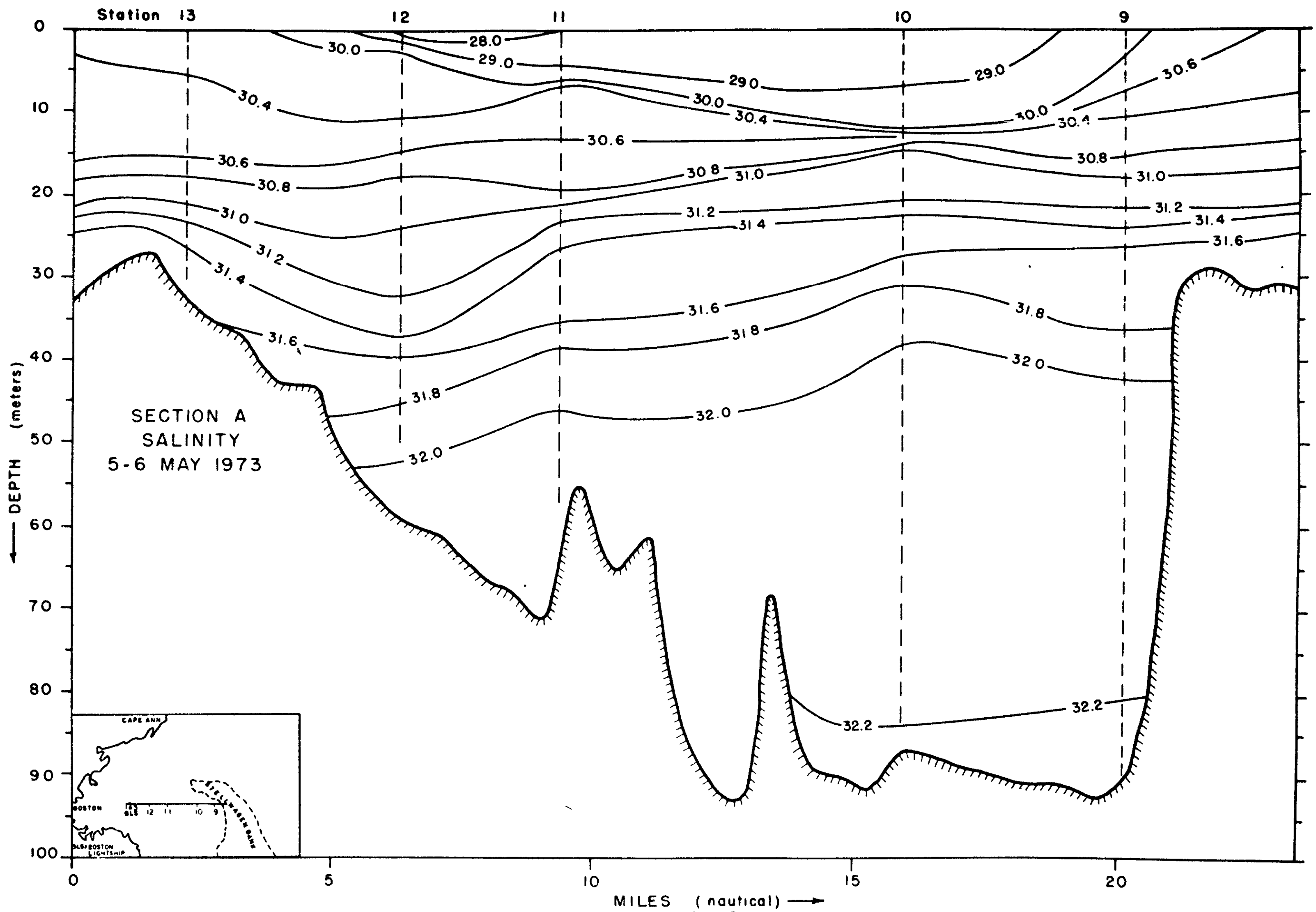

Station
28
31
23
24
30.6
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
SECTION C
SALINITY
21-22 APRIL 1973
DEPTH (meters)
MILES (nautical)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
CAPE ANN
BOSTON
BOSTON LIGHTSHIP
STELLWAGEN BANK

Figure 3.11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9
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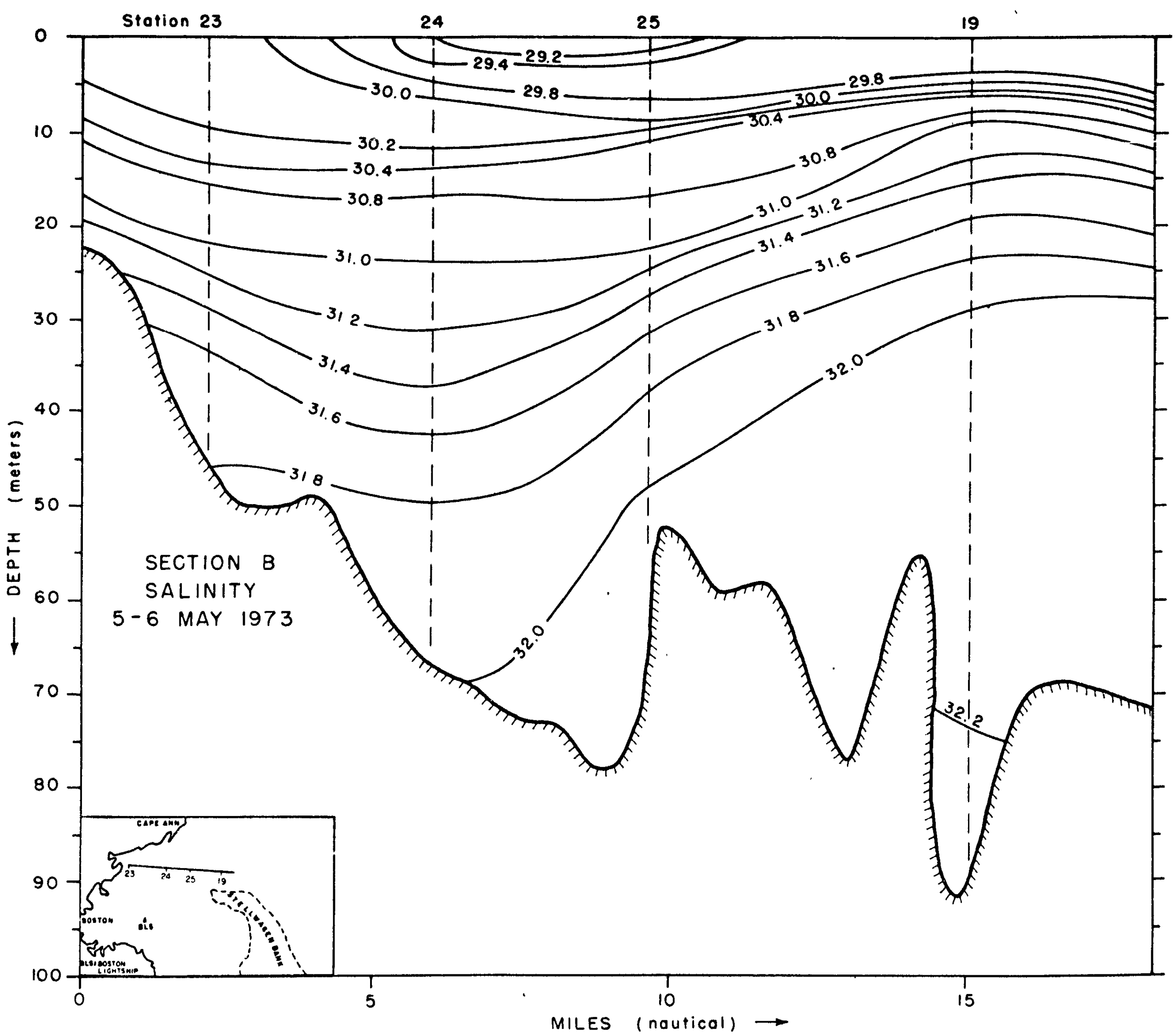
29.0
29.0
29.0
30.4
30.0
30.4
30.0
30.4
30.6
30.6
30.6
30.8
30.8
30.8
31.0
31.0
31.0
31.2
31.2
31.2
31.4
31.4
31.4
31.6
31.6
31.6
31.8
31.8
31.8
32.0
32.0
32.0
32.2
32.2
SECTION A
SALINITY
5-6 MAY 1973
DEPTH (meters)
MILES (nautical)
CAPE ANN
BOSTON
BOSTON LIGHTSHIP
STELLWAGEN BANK

Figure 3.12


Station 23
24
25
19
SECTION B
SALINITY
5-6 MAY 1973
DEPTH (meters)
MILES (nautical)
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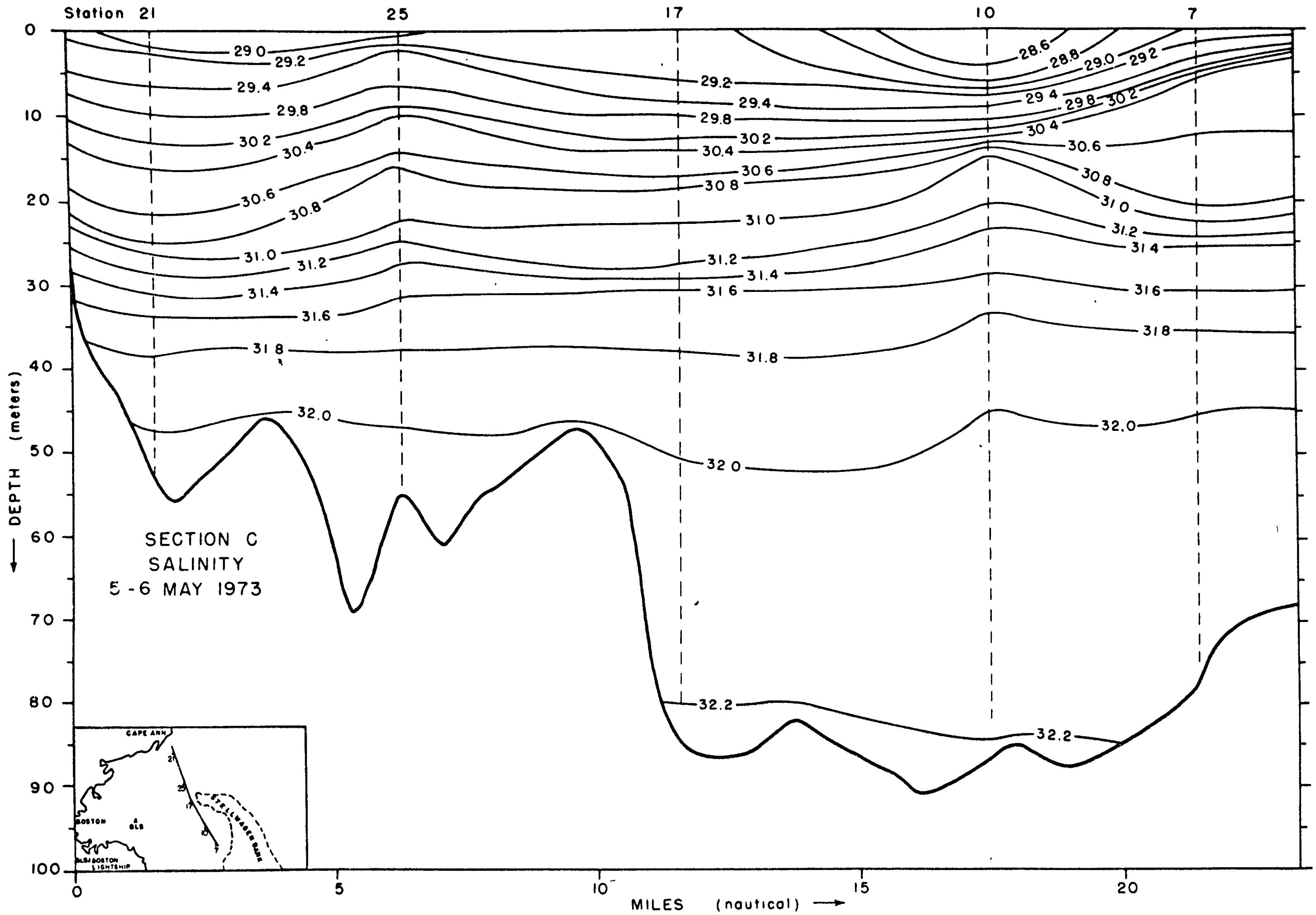
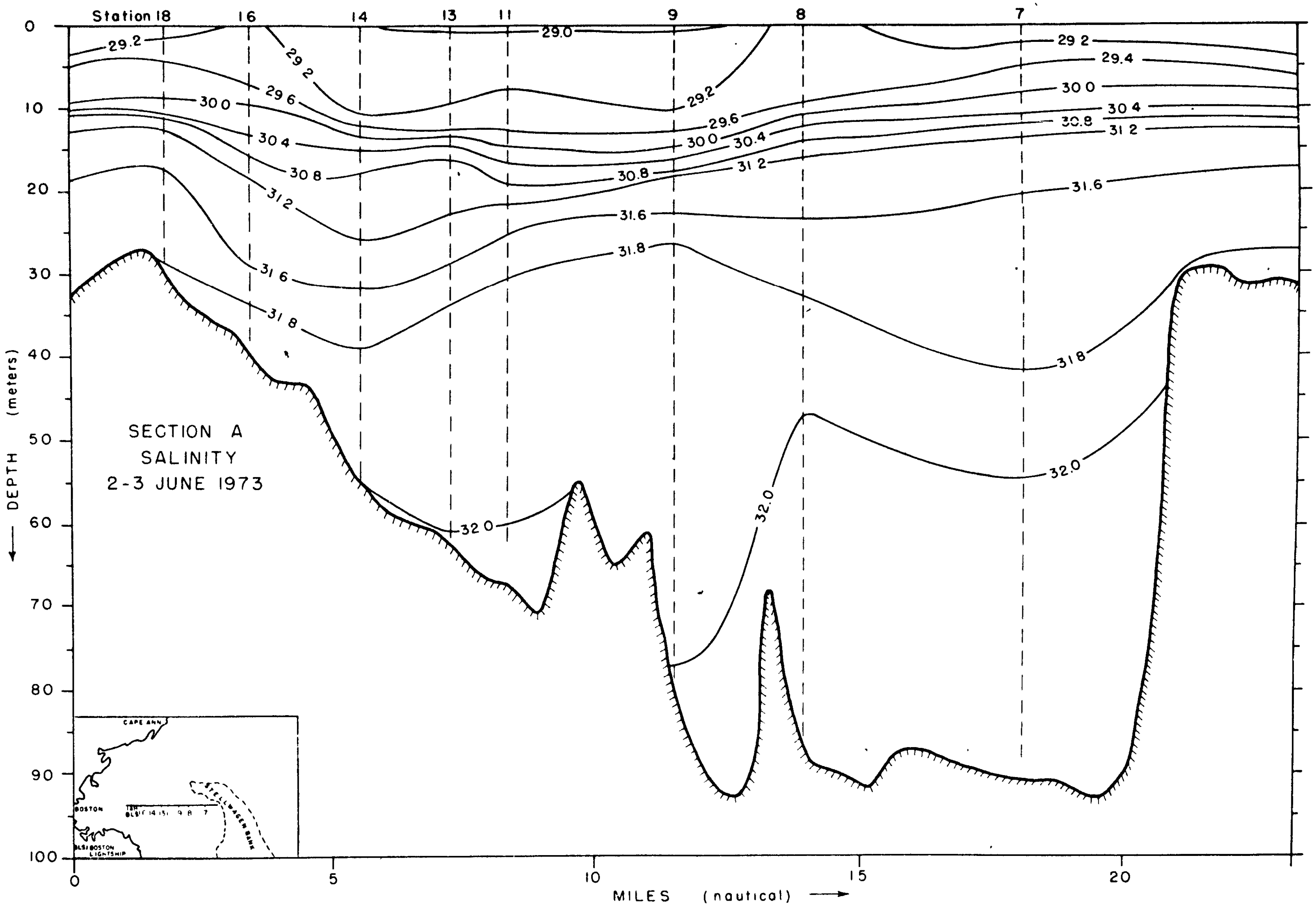
29.8
30.0
30.2
30.4
30.8
31.0
31.2
31.4
31.6
31.8
32.0
32.2
CAPE ANN
BOSTON

Figure 3.13



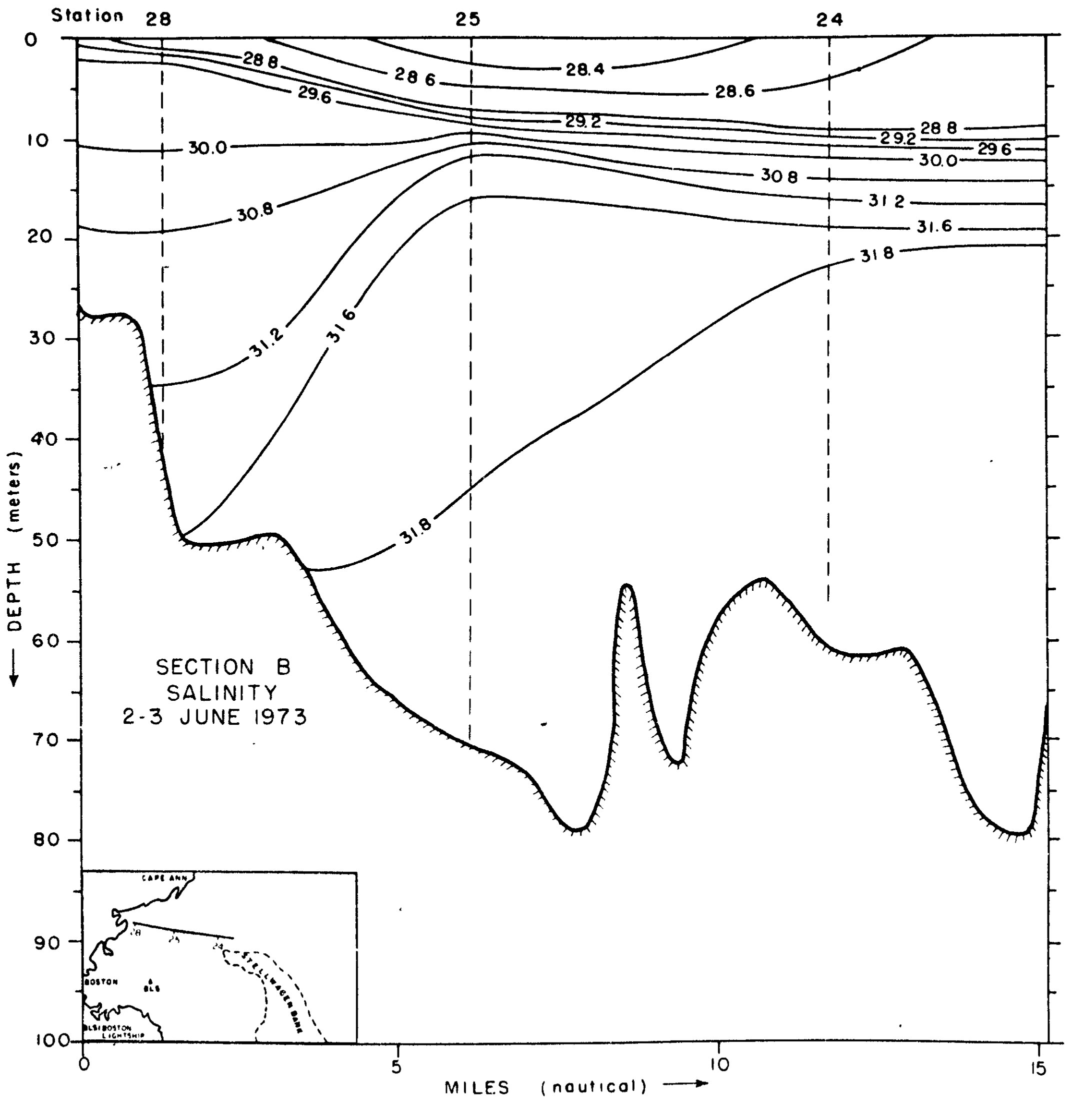
Station 21
25
17
10
7
DEPTH (meters)
MILES (nautical)
SECTION C
SALINITY
5-6 MAY 1973
CAPE ANN
BOSTON
BOSTON LIGHTSHIP
STELLWAGEN BANK

Figure 3.14



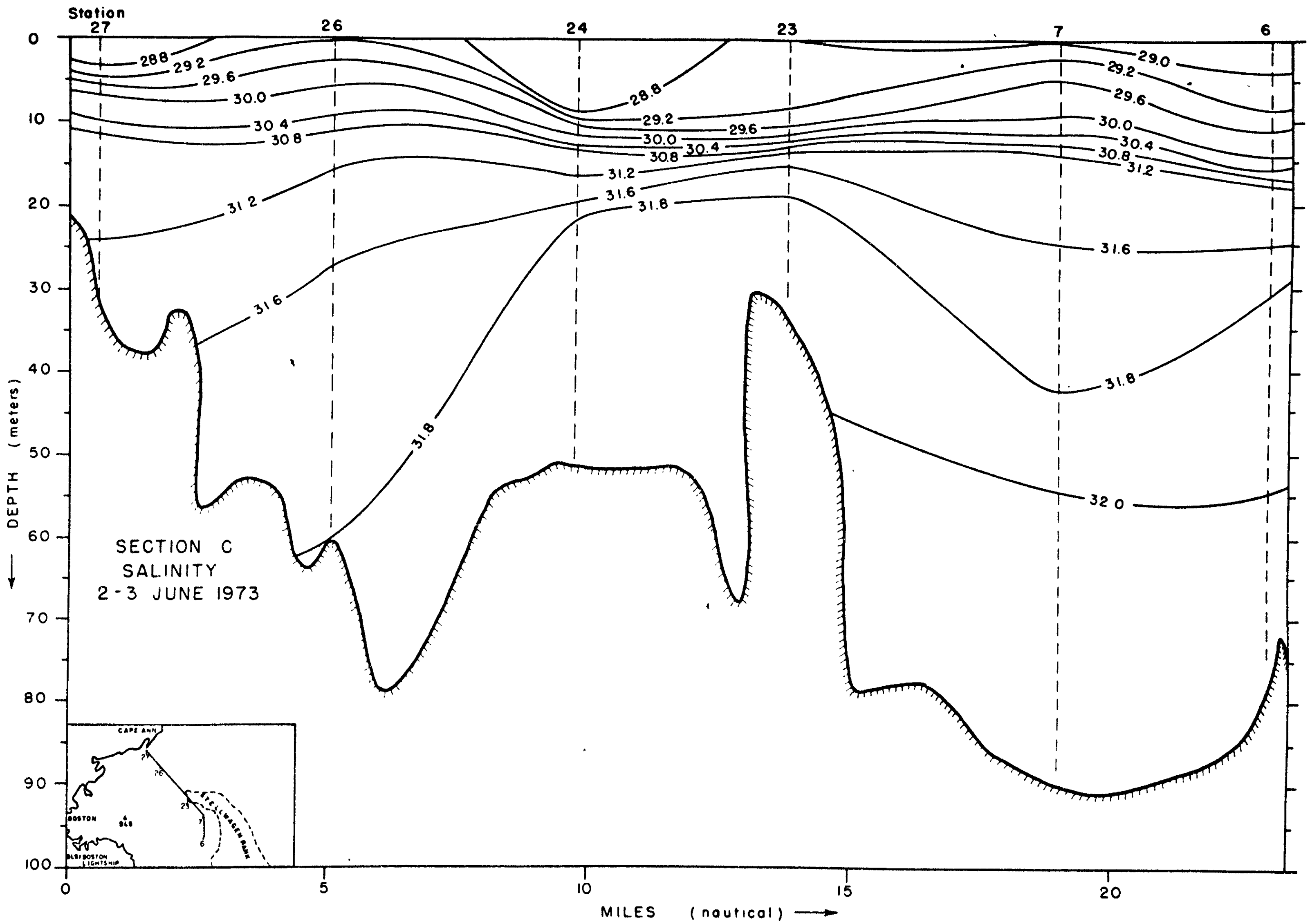
Station 18
16
14
13
11
9
8
7
29.0
29.2
29.4
29.6
30.0
30.4
30.8
31.2
31.6
31.8
32.0
SECTION A
SALINITY
2-3 JUNE 1973
DEPTH (meters)
MILES (nautical)
CAPE ANN
BOSTON
STELLWAGEN BANK
BOSTON LIGHTSHIP

Figure 3.15



Station 28
25
24
28.8
28.6
28.4
28.6
29.6
29.2
28.8
29.2
29.6
30.0
30.0
30.8
30.8
31.2
31.2
31.6
31.6
31.8
31.8
SECTION B
SALINITY
2-3 JUNE 1973
DEPTH (meters)
MILES (nautical)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
CAPE ANN
BOSTON
STELLWAGEN BANK
BOSTON LIGHTSHIP

Figure 3.16


Station
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26
24
23
7
6
SECTION C
SALINITY
2-3 JUNE 1973
DEPTH (meters)
MILES (nautical)
28.8
29.0
29.2
29.6
30.0
30.4
30.8
31.2
31.6
31.8
32.0
CAPE ANN
BOSTON
BLS
BLS: BOSTON LIGHTSHIP
STELLWAGEN BANK

Figure 3.17

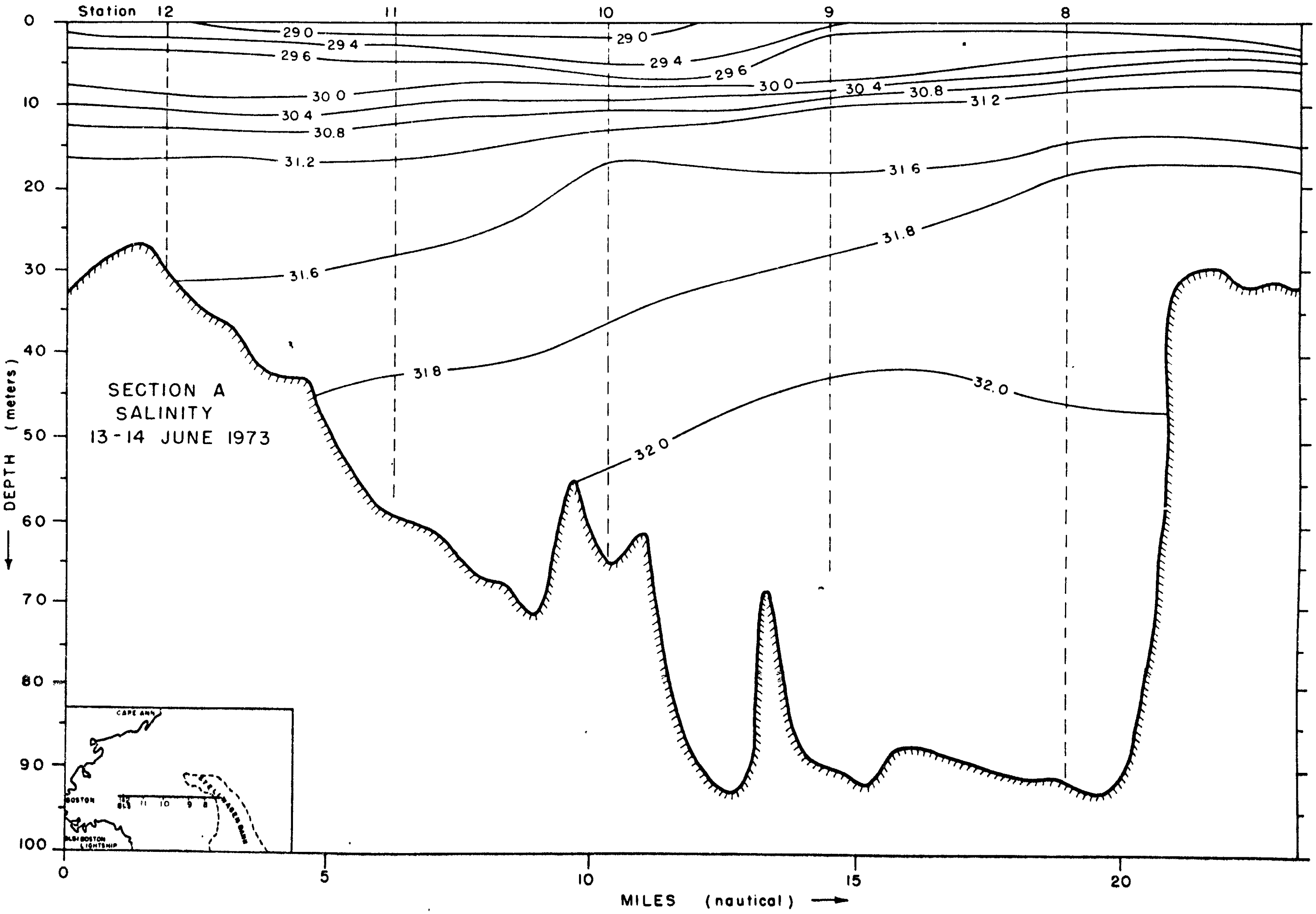
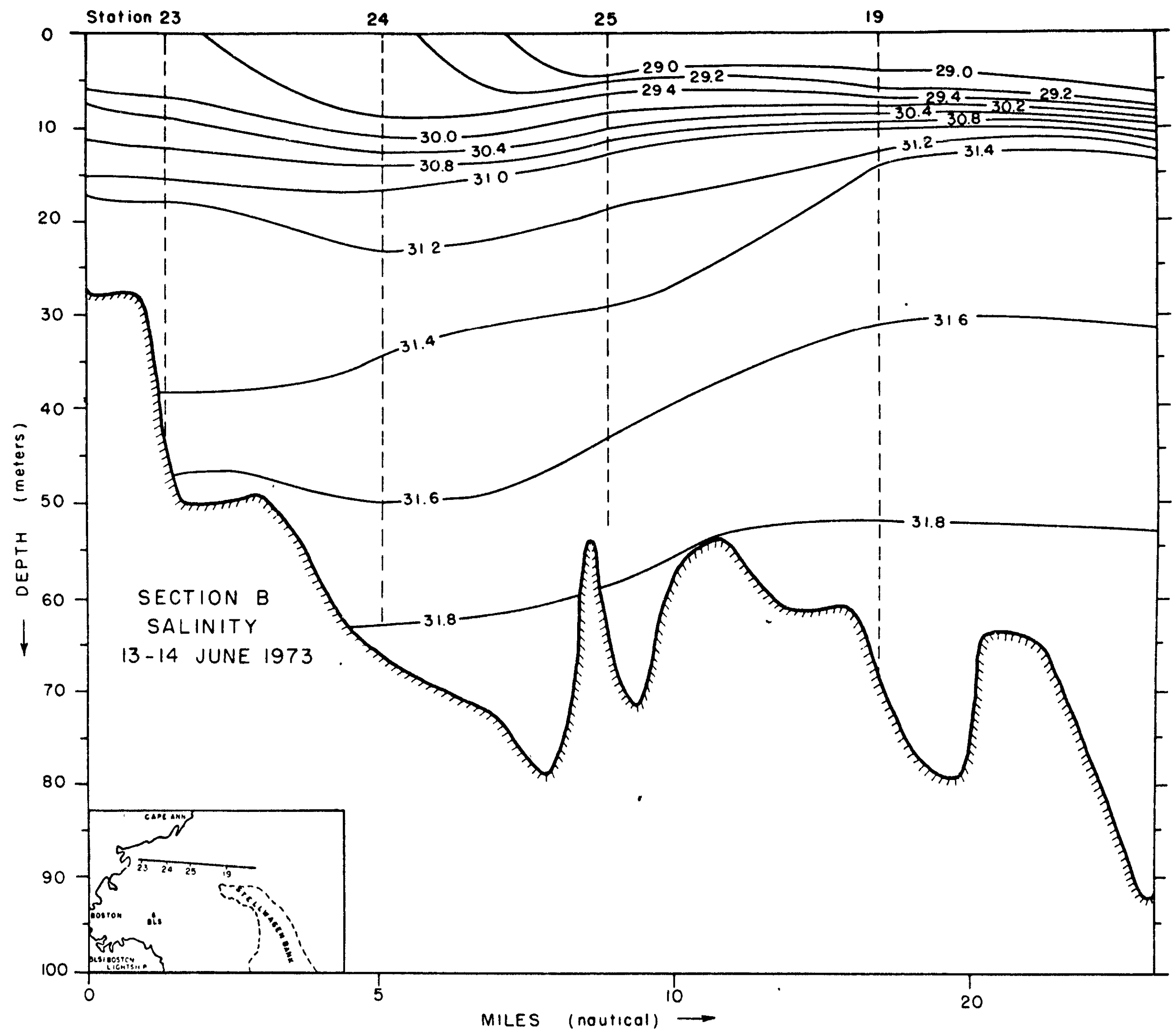
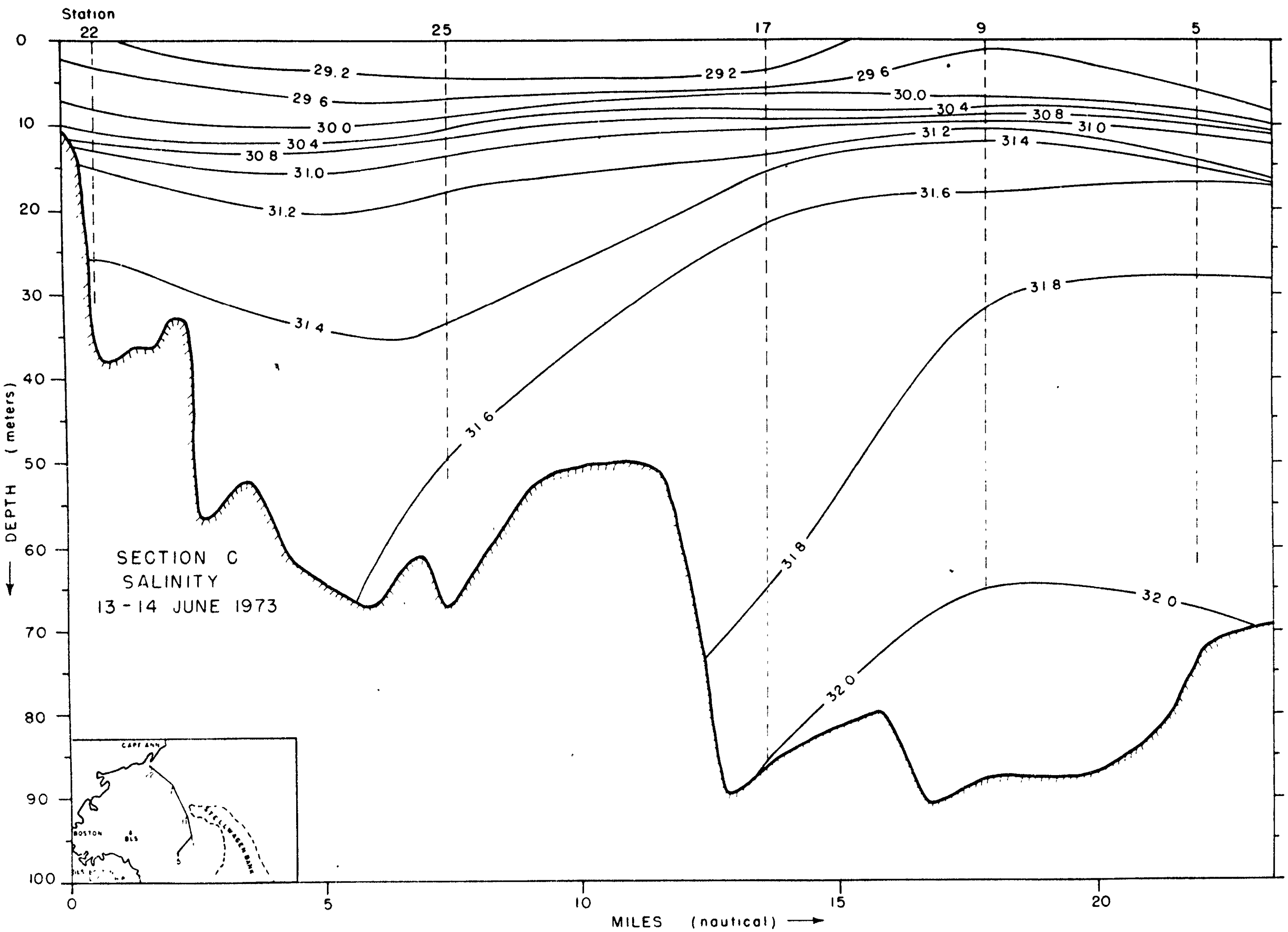

Station 12
11
10
9
8
29.0
29.4
29.6
30.0
30.4
30.8
31.2
31.6
31.8
32.0
SECTION A
SALINITY
13-14 JUNE 1973
DEPTH (meters)
MILES (nautical)
CAPE ANN
BOSTON
BOSTON LIGHTSHIP

Figure 3.18



Station 23
24
25
19
SECTION B
SALINITY
13-14 JUNE 1973
DEPTH (meters)
MILES (nautical)
29.0
29.2
29.4
30.0
30.2
30.4
30.8
31.0
31.2
31.4
31.6
31.8
0
10
20
30
40
50
60
70
80
90
100
5
CAPE ANN
BOSTON
STELLWAGEN BANK

Figure 3.19



Station
22
25
17
9
5
DEPTH (meters)
MILES (nautical)
29.2
29.6
30.0
30.4
30.8
31.0
31.2
31.4
31.6
31.8
32.0
SECTION C
SALINITY
13 - 14 JUNE 1973
CAPE ANN
BOSTON

Figure 3.20

CHAPTER 4

VOLUMETRIC DETERMINATION OF FRESH WATER IN THE BAY

In retrospect, it was rather unfortunate that the first planned cruise of 14-15 March had to be aborted due to rough weather and equipment failure; since by the time of the first actual cruise two weeks later the homogeneous conditions, typical of the Bay in winter (Bigelow, 1927), had been eroded. Because of this we have no actual record of the base salinity of the water of the Bay with which the fresh water from the rivers mixed.

For this study the homogeneous winter salinity of the water of the Bay was assumed to be 32.2 $^{0}/00$. There are many reasons that led to the choosing of 32.2 $^{0}/00$ water for the winter salinity; it is observed that the bottom waters of the Bay at 29-30 March had a salinity of 32.2 $^{0}/00$ (See Fig. 3.6). In Fig. 3.1 it is seen that the patch of high salinity water in the middle of the Bay on 29-30 March is centered at station 17 of that cruise, the variation of salinity at depth at this point is shown in Appendix C, Fig. 1.

It is observed that the salinity changes from 31.7 $^{0}/00$ at the top to 32.2 $^{0}/00$ at the bottom; a similar observation is noted at station 11 (See Appendix C, Fig. 2) which is also in this pool of high salinity water. This difference of only .5 $^{0}/00$ from top to bottom contrasts greatly with the other stations of this cruise, where the variation from top to bottom is of the order of 1.1 $^{0}/00$ for example stations 16 and 18, just 7 km to the West and East respectively of station 17, (See Appendix C, Figs. 3 and 4).

Chase (1969) shows that the average surface salinity at the Boston Lightship over a 12 year period (1956-1967) was 32.2 $^0/00$. This reinforces the belief that the winter homogeneous salinity for 1973 was 32.2 $^0/00$ and that the error in this figure is no more than the error in determining the average salinity of the Bay from the vertical casts. In any case, the choice of the "base-line" salinity in no way affects the volume of fresh water added between any two cruises, although it does affect the total amount of fresh water believed to be in the Bay.

To determine the amount of fresh water in the Bay, a method similar to that used by Ketchum and Keen (1955) to determine the accumulation of river water on the continental shelf between Cape Cod and Chesapeake Bay was used. The Bay was divided into four sections, A, B, C, and D, See Figure 4.1. The volume of each section was determined by use of the depth readings on the U.S. Coast and Geodetic Survey Navigation Chart #1207. These values are shown in Table 4.1.

The depth mean salinity was then determined for each section (See Tables 4.2 - 4.6) by finding the average salinity in the water column at each station in the section. The fraction of fresh water in the Bay, f, at any given time is given by,

$$f = \frac{S_o - \bar{S}}{S_o} \qquad 4.1$$

where S_o is the original salinity of the water in the Bay; $\bar{S}$, the average salinity in the Bay at the given time, Ketchum and Keen (1955). This model assumes that the total volume of water in the Bay remains constant, as the fresh water is added. This assumption is a reasonable one since the amount of fresh water in the Bay was always less than 3% of the total volume of water in the Bay.

To determine the volume of fresh water in each section, the fraction of fresh water was multiplied by the total volume of each section (See Tables 4.2 - 4.6). The sum of the fresh water in each section gave the total amount of fresh water in the Bay. The total volume of fresh water in the Bay at the time of any given cruise was subtracted from the volume there at the time of the previous cruise to obtain the volume of fresh water added to the Bay during the time between the two cruises, Tables (4.2 - 4.6).

Computing the average salinity of a volume of water as large and as irregularly shaped as Massachusetts Bay is at best a rough estimate. Since a vertical profile was obtained on the average of every 7 km on each of these cruises (See Fig. 3.1 -3.5) a fairly good estimate was made. This estimate is believed to be accurate to ± .05 $^0/00$. However, since in determining the fraction of fresh water (Eqn. 4.1) a difference between two large numbers is required, it is believed that the fresh water volume is accurate to within 25% at the time of the first cruise when the salinity difference is small, and to within 10% at the time of the last three cruises when the salinity difference is much greater (Tables 4.2 - 4.6). The volume of fresh water present in the Bay, at any given time, is shown in Fig. 4.2.

The daily discharge of water was plotted for the Neponset, Charles and Mystic Rivers, the Mother Brook and the Deer Island Sewerage treatment plant, as the sources of fresh water which empty into the Bay directly

TABLE 4.1

VOLUME OF BAY

	A	B	C	D	Total
Volume ($m^3 \times 10^6$)	15,420	21,264	19,404	22,405	78,493

TABLE 4.2

VOLUME OF FRESH WATER IN BAY, 29-30 MARCH, 1973

Section	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/_{00}$	31.7	31.8	31.8	31.9	
Fraction Fresh (f)	.0155	.0124	.0124	.0093	
Volume of Fresh Water ($m^3 \times 10^6$)	239	264	241	208	952

TABLE 4.3

VOLUME OF FRESH WATER IN BAY, 21-22 APRIL 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/_{00}$	31.5	31.45	31.35	31.30	
Fraction Fresh (f)	.0217	.0232	.0263	.0280	
Volume of Fresh Water ($m^3 \times 10^6$)	335	493	510	627	1965
Volume Added between 29-30 March to 21-22 April ($m^3 \times 10^6$)	106	229	269	419	1047

TABLE 4.4

VOLUME OF FRESH WATER IN BAY, 5-6 MAY 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/_{00}$	31.25	31.30	31.20	31.25	
Fraction Fresh (f)	.0295	.0280	.0311	.0295	
Volume of Fresh Water ($m^3 \times 10^6$)	455	595	604	661	2,315
Volume Added between 21-22 April to 5-6 May ($m^3 \times 10^6$)	120	102	94	34	350

TABLE 4.5

VOLUME OF FRESH WATER IN BAY, 2-3 JUNE 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/00$	31.25	31.25	31.25	31.15	
Fraction Fresh (f)	.0295	.0295	.0295	.0326	
Volume of Fresh Water ($m^3 \times 10^6$)	455	627	572	730	2,384
Volume Added between 5-6 May to 2-3 June ($m^3 \times 10^6$)	0	32	-32	69	69

TABLE 4.6

VOLUME OF FRESH WATER IN BAY, 13-14 JUNE 1973

	A	B	C	D	Total
Average Salinity ($\bar{S}$) $^0/00$	31.10	31.15	31.30	31.35	
Fraction Fresh (f)	.0342	.0311	.0280	.0264	
Volume of Fresh Water ($m^3 \times 10^6$)	527	661	543	592	2,323
Volume Added between 2-3 June to 13-14 June ($m^3 \times 10^6$)	72	34	-29	-138	-61

(See Fig. 4.3 - 4.7). This data, except for the Deer Island treatment plant, was obtained from the U.S. Geological Survey. Unfortunately, for certain rivers the values for part of May and for June was not yet available. When this occurred, if there were any values for that month, the average for the month was used, and if there were no readings available for the month, the average for the same month for the previous year, 1972, was used. The periods for which this occurred are clearly marked in Fig. 4.3 - 4.7 and Fig. 4.9 - 4.11.

Similarly, the daily flow rate of the rivers which originate north of Cape Ann and come into Massachusetts Bay, the Merrimac, Parker, and Ipswich Rivers, were plotted in Fig. 4.9 - 4.11. The total daily flow rate from these rivers is shown in Fig. 4.12. The salinity of the river water is taken as 0 ^{0}/00, being at most .1 ^{0}/00, John Edmonds (1973). The daily flow rates shown in Fig. 4.3 - 4.13 have been corrected for the drainage area which lie below the position of the gauging stations. The correction factors used, obtained from Mr. G. Searles at the Geological Survey, together with the gauged drainage area and total drainage area are shown in Table 4.7.

The data for the Deer Island sewerage treatment plant was obtained from the plant at Deer Island. The measured salinity during the period January - June, 1973, of the Deer Island water was 5.5 ^{0}/00. Therefore, this volume of water was divided into two components, of 0 ^{0}/00 and 32.2 ^{0}/00 salinity respectively. The 0 ^{0}/00 component constitutes the effective fresh water present in the Deer Island discharge, while the 32.2 ^{0}/00 component would have no effect on the Bay since 32.2 ^{0}/00 was

TABLE 4.7

CORRECTION FACTORS FOR RIVER DISCHARGE

River	Drainage Area above Gauging Station	Total Drainage Area	Correction Factor
Merrimac	4,633	5,006	1.08
Parker	21.5	65	3.00
Ipswich	124	155	1.25
Mystic	23	65	2.5
Charles	251	299	1.2
Neponset	62.4	117	2.0
*Mother Brook	251*	299*	1.2

*The Mother Brook is partly a man made canal linking the Charles River with the Neponset River, but the gauging station on the Charles does not record the amount of water flowing through the Mother Brook, hence the same correction factor as for the Charles River is used.

taken as the original salinity of the Bay. The total daily flow of fresh water from sources which empty into the Bay directly is shown in Fig. 4.8. In Fig. 4.13 the total daily flow from the Merrimac, Parker and Ipswich rivers originating north of Cape Ann, together with the measured sources of fresh water which empty into the Bay directly is plotted.

In order to compare the volume of fresh water in the Bay with the discharge of the rivers it was necessary to determine the time lag between the time the water left the river and the time it got into the Bay. For the case of the rivers which empty into the Bay directly, the time lag would be zero. This, however, would not be the case for rivers north of Cape Ann. Since by far the largest contribution to the total flow (Fig. 4.13) is the Merrimac (Fig. 4.9), it is essential that a good estimate of this time lag is obtained.

By aligning the maximum flow rate for the rivers north of Cape Ann (Fig. 4.12) with the maximum volume of fresh water in the Bay (Fig. 4.2) a time lag of 20 days was determined. This figure of 20 days compares favorably with the drift bottle measurements of Day (1958), Bumpus (1961) and Graham (1970) all of whom gave a surface drift of between 2 - 4 km/day. Having thus obtained the time lag, between the time the water left the mouth of the rivers north of Cape Ann and the time it arrived in the Bay, to determine the fresh water discharge by the rivers for any given period; for the rivers north of Cape Ann the discharge in the period 20 days beforehand was taken.

It was also necessary to determine, at what rate the Bay was losing the fresh water it contained. By examination of Fig. 3.1 - 3.5 it seemed that the Bay lost the fresh water not by advection out of the Bay, but by diffusion of salt into the Bay. Although an influx of salt is mainly responsible for the disappearance of the fresh water, this will still be termed as a loss of fresh water. In Fig. 4.2 of the volume of fresh water in the Bay versus time, it is observed that the volume of fresh water in the Bay reaches a maximum of 2,450 x 10^6 m^3 on May 25. Since on this date the volume of fresh water in the Bay was neither increasing nor decreasing, it meant that the volume of fresh water added to the Bay was equal to the volume of fresh water being lost. When the twenty day lag was taken into account, it means that for the rivers north of Cape Ann the discharge of May 5 was required. Unfortunately in the period from 30 April - 8 May no readings were recorded for the Merrimac and the average discharge for the month of May had to be used to determine the flow on May 5. The value so obtained is shown in Table 4.8.

The rate of diffusion of salt into the Bay would be dependent on the total volume of fresh water in the Bay. Assuming that this is a linear relationship which is consistent with the total mixing model used in computing the volume fresh water, the average loss per day over any given time period is obtained from the average volume of fresh water in the Bay over that period. In Table 4.8 the values of volume of fresh water added in the periods between each cruise as calculated from the volume of river run-off, together with the volume of water observed to be added, computed from the average salinity of the Bay are shown. There is surprisingly good correspondence between both values, their discrepancy at no time being greater than the possible percentage error in determining the total volume of fresh water in the Bay by the method of Ketchum and Keen (1955).

TABLE 4.8

VOLUME OF FRESH WATER IN BAY

Time Period	Average Volume in Bay $(m^3 \times 10^6)$	Average Loss Per Day $(m^3 \times 10^6)$	Period (days)	Total Loss (L) $(m^3 \times 10^6)$	River Flow Volume (R) $(m^3 \times 10^6)$	Volume Added to Bay Using River Data (R-L) $(m^3 \times 10^6)$	Volume Added to Bay Using Method of Ketchum and Keen $(m^3 \times 10^6)$
May 25	2,450	50.8	1	50.8	50.8	0	0
29-30 March to 21-22 April	1,476	30.6	23	704	1,671	976	1,047
21-22 April to 5-6 May	2,157	44.7	14	655	1,281	626	587
5-6 May to 2-3 June	2,354	48.8	28	1,366	1,278	-88	69
2-3 June to 13-14 June	2,354	48.8	11	537	626	89	-61

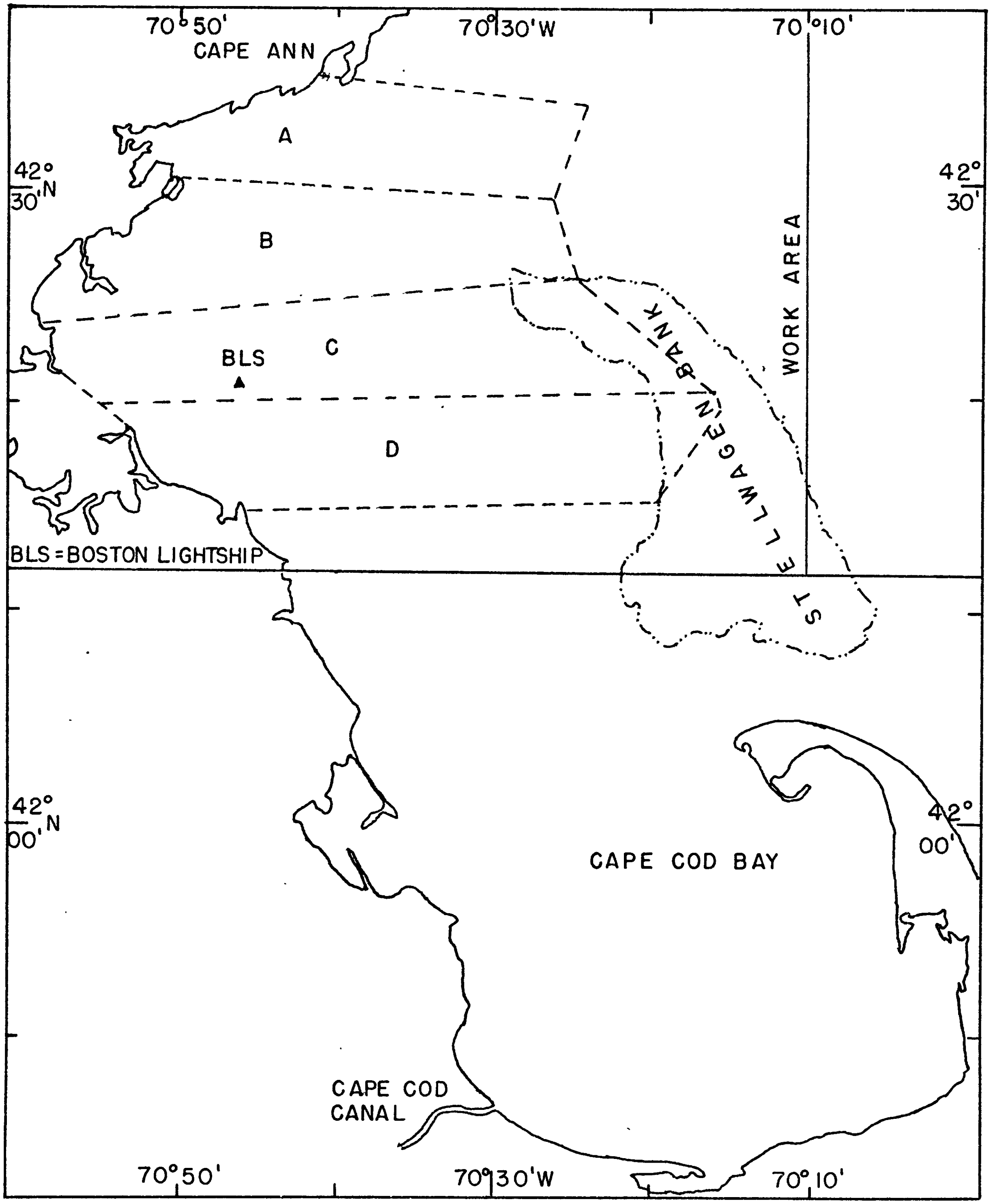


Figure 4.1: Map of Massachusetts Bay showing Region of Work and Sections into which Bay was divided to compute the Volume of Fresh Water

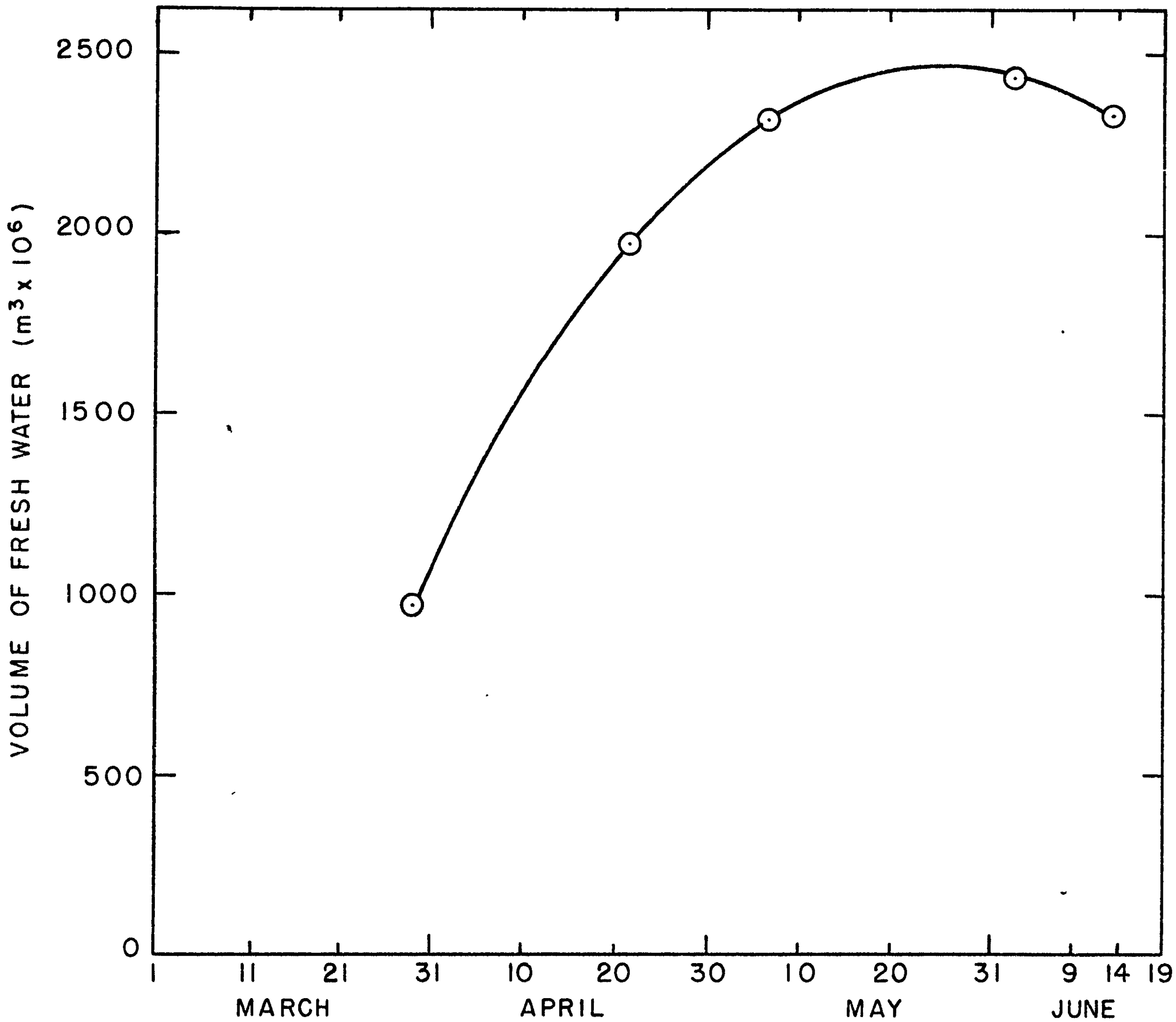


Figure 4.2: Total Volume of Fresh Water in Bay vs Time

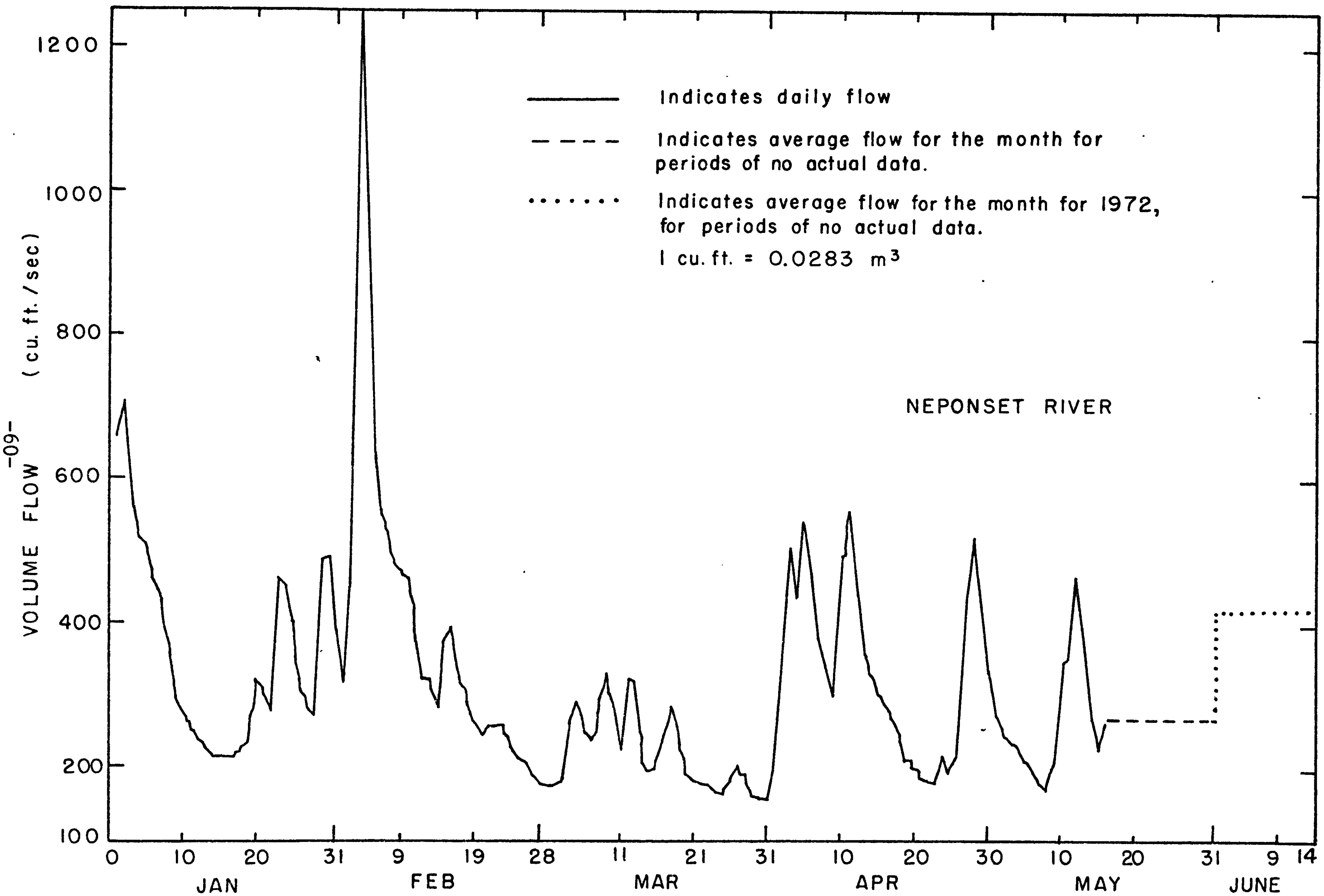


Figure 4.3: Daily Volume Flow of Neponset River

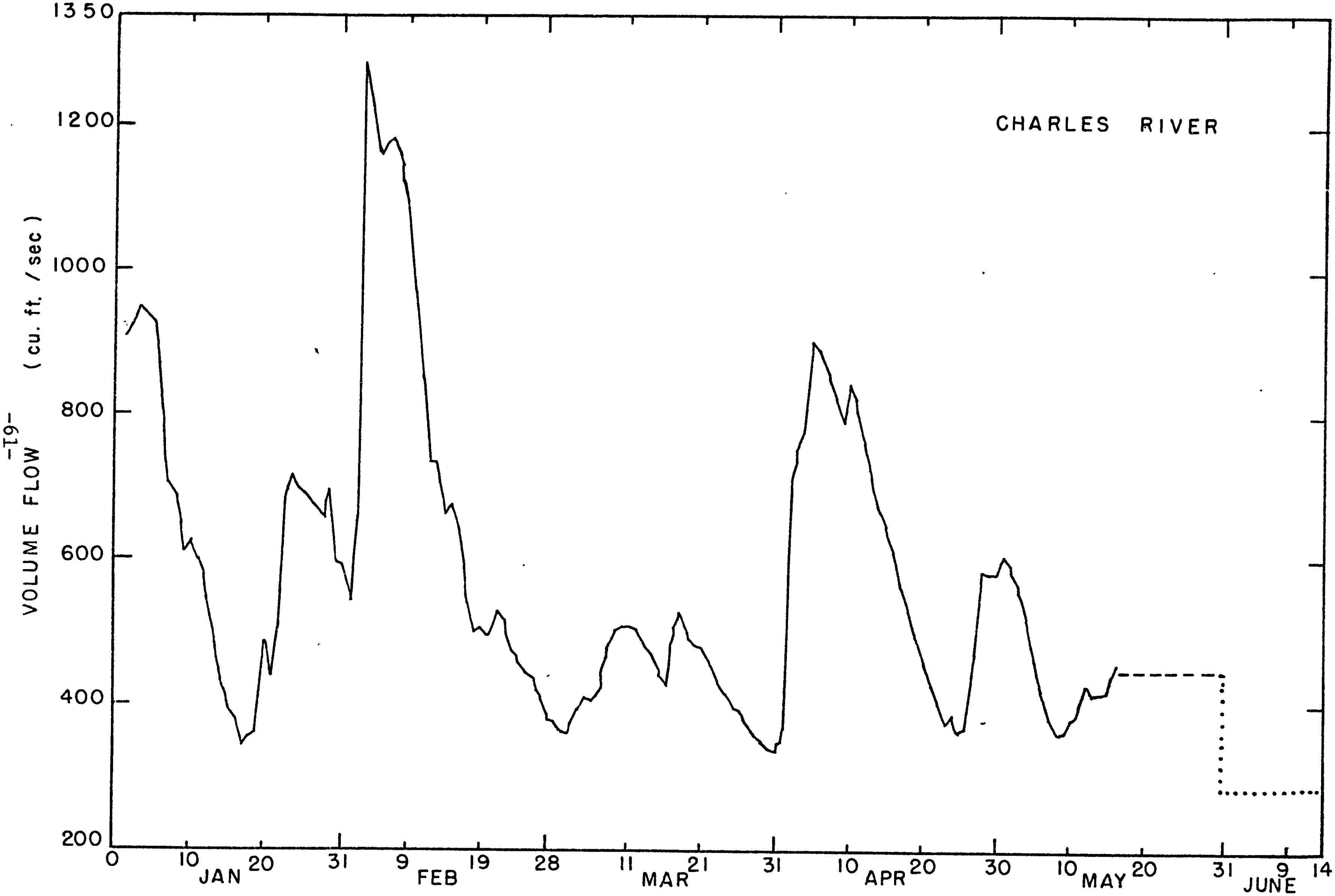


Figure 4.4: Daily Volume Flow of Charles River

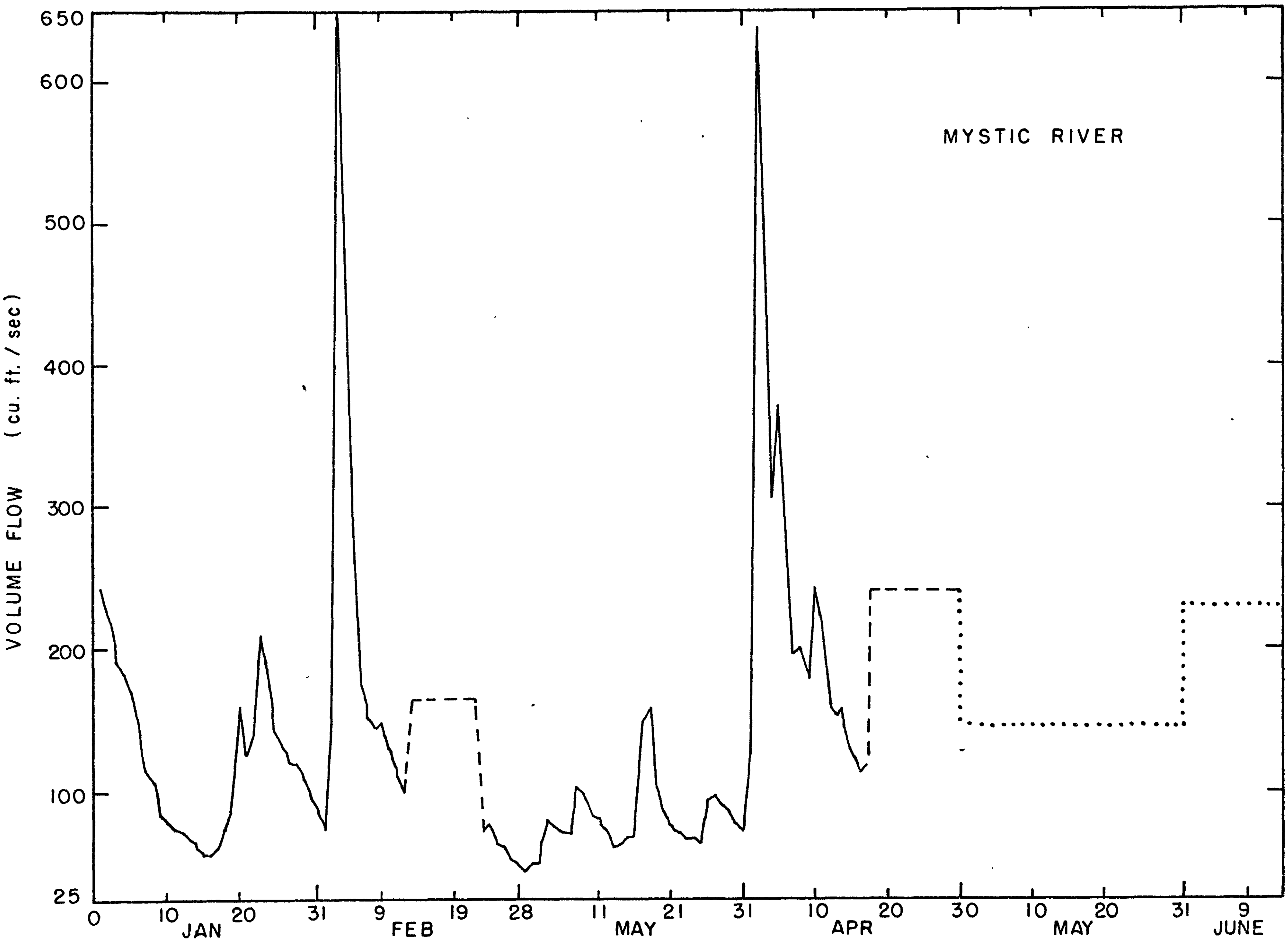


Figure 4.5 Daily Volume Flow of Mystic River

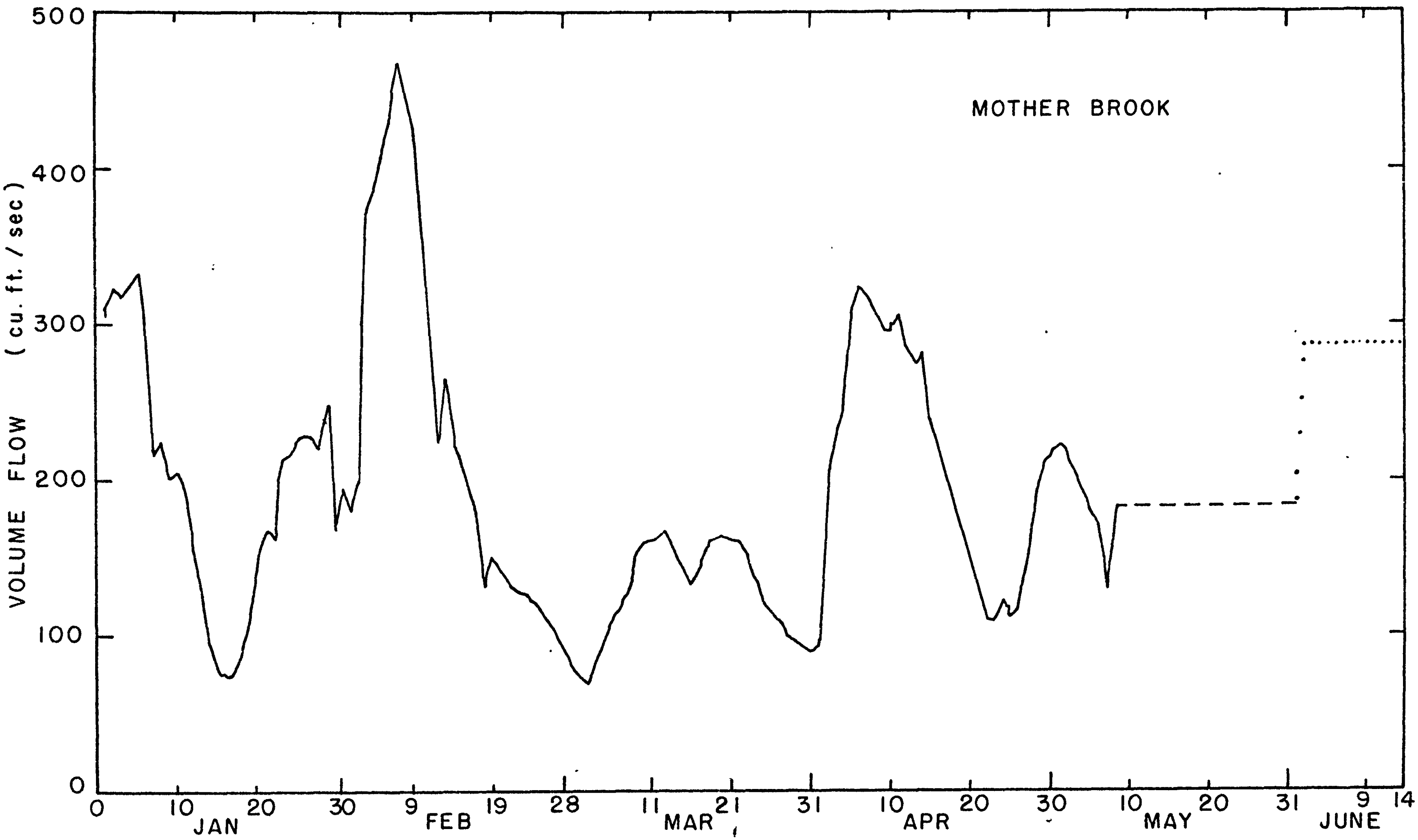


Figure 4.6: Daily Volume Flow of Mother Brook

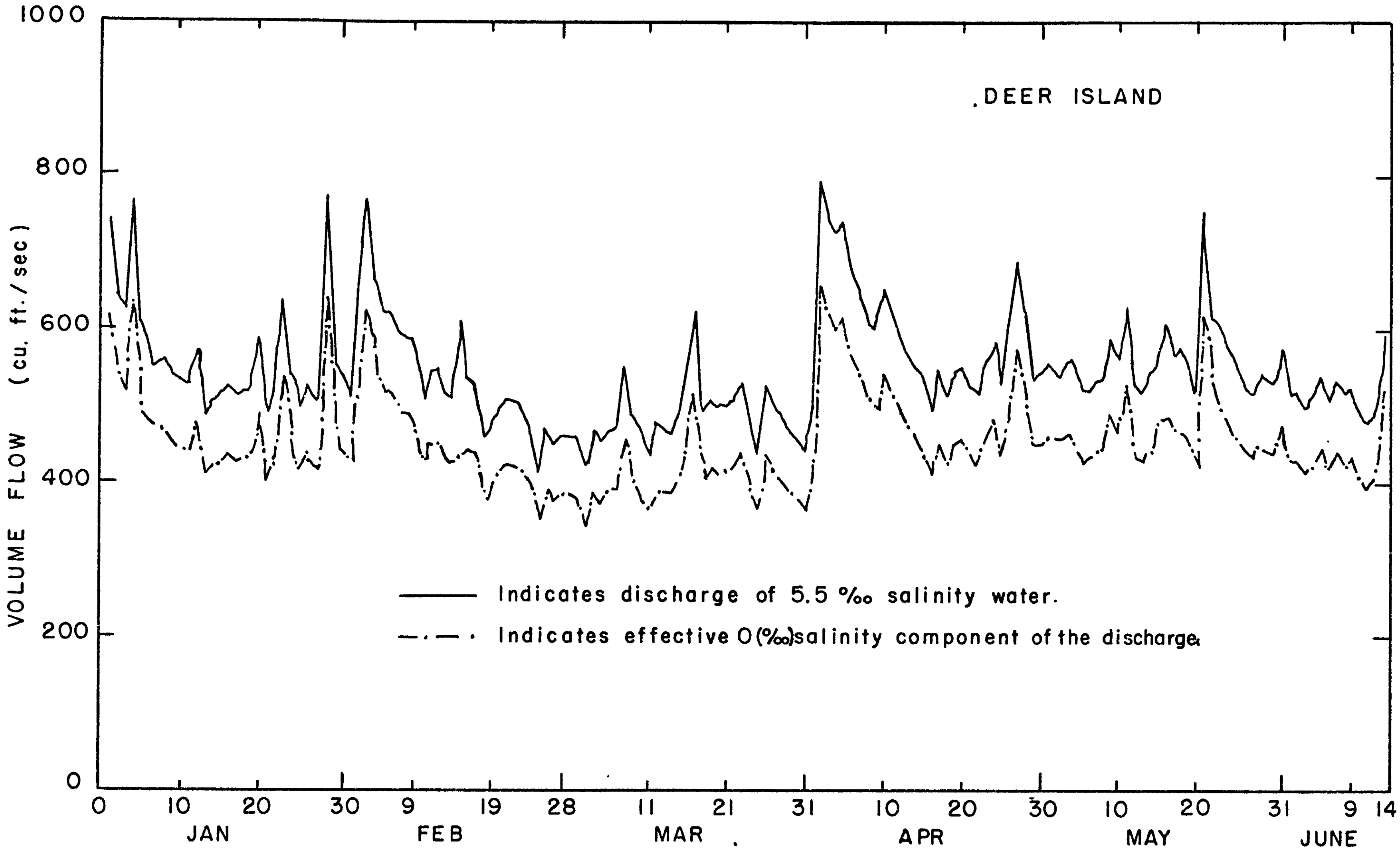


Figure 4.7: Daily Volume Flow of Deer Island Sewerage Treatment Plant

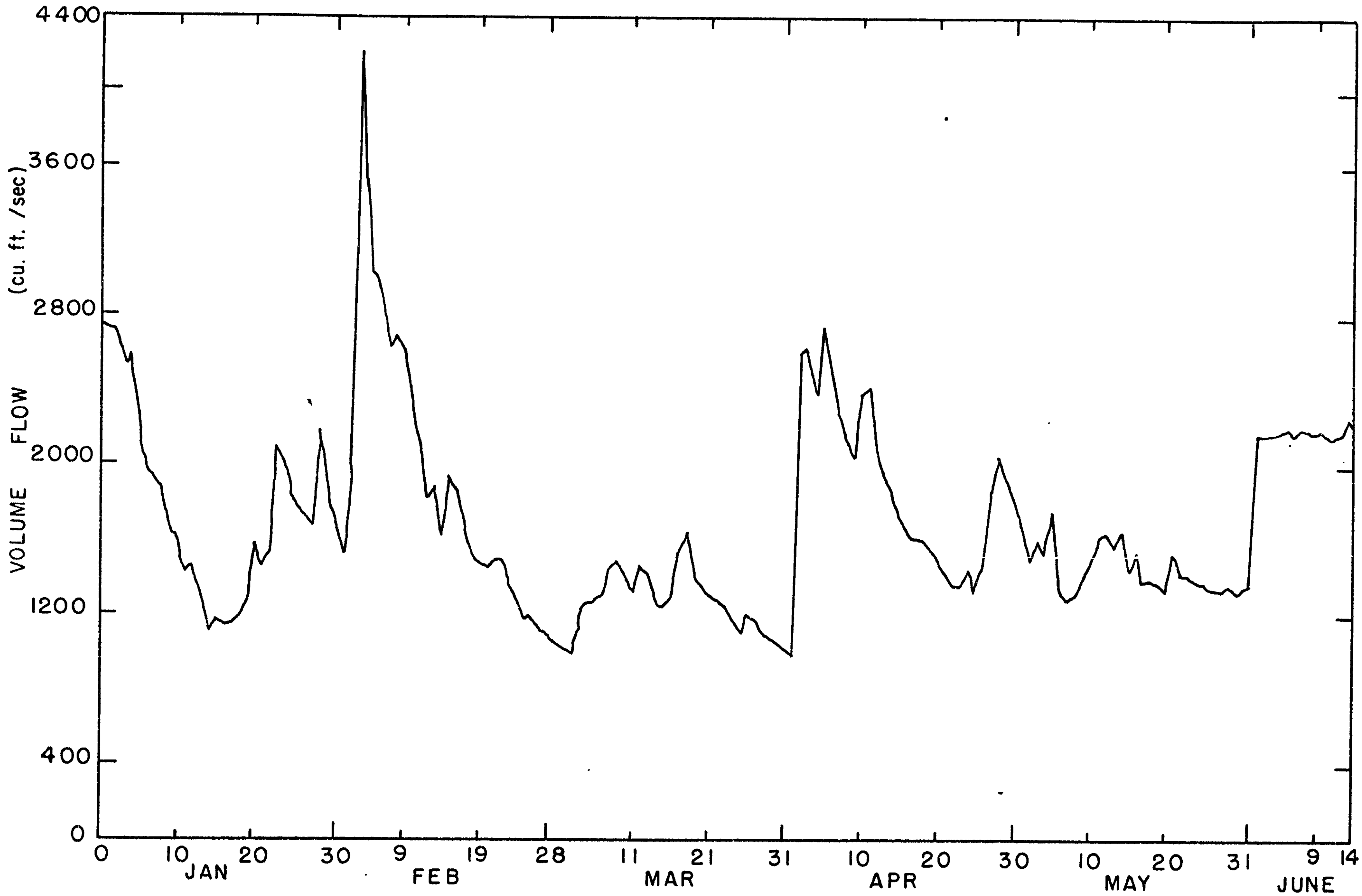


Figure 4.8: Daily Volume Flow of Fresh Water into Massachusetts Bay from Sources Which Empty into the Bay Directly

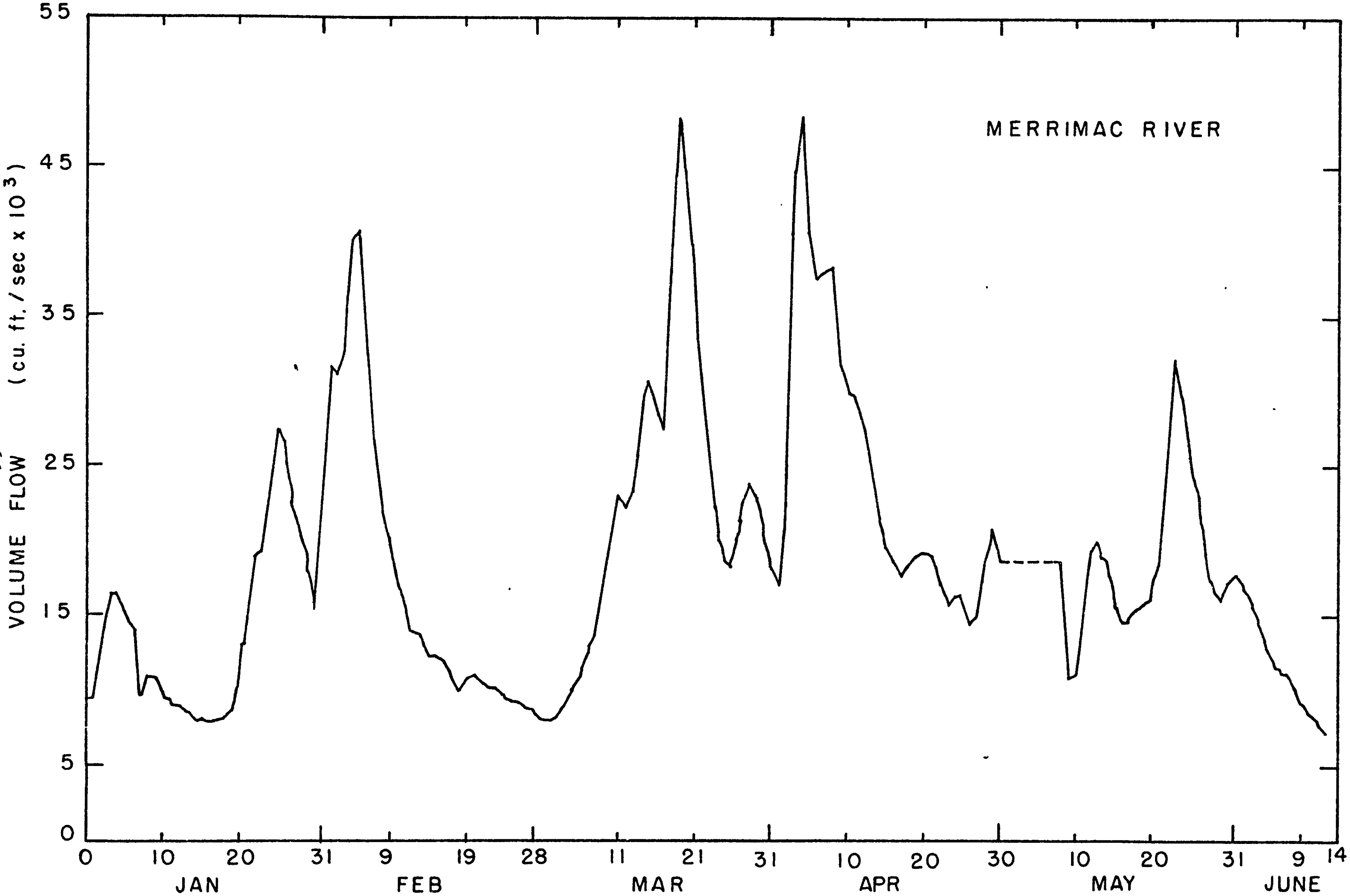


Figure 4.9: Daily Volume Flow of Merrimac River

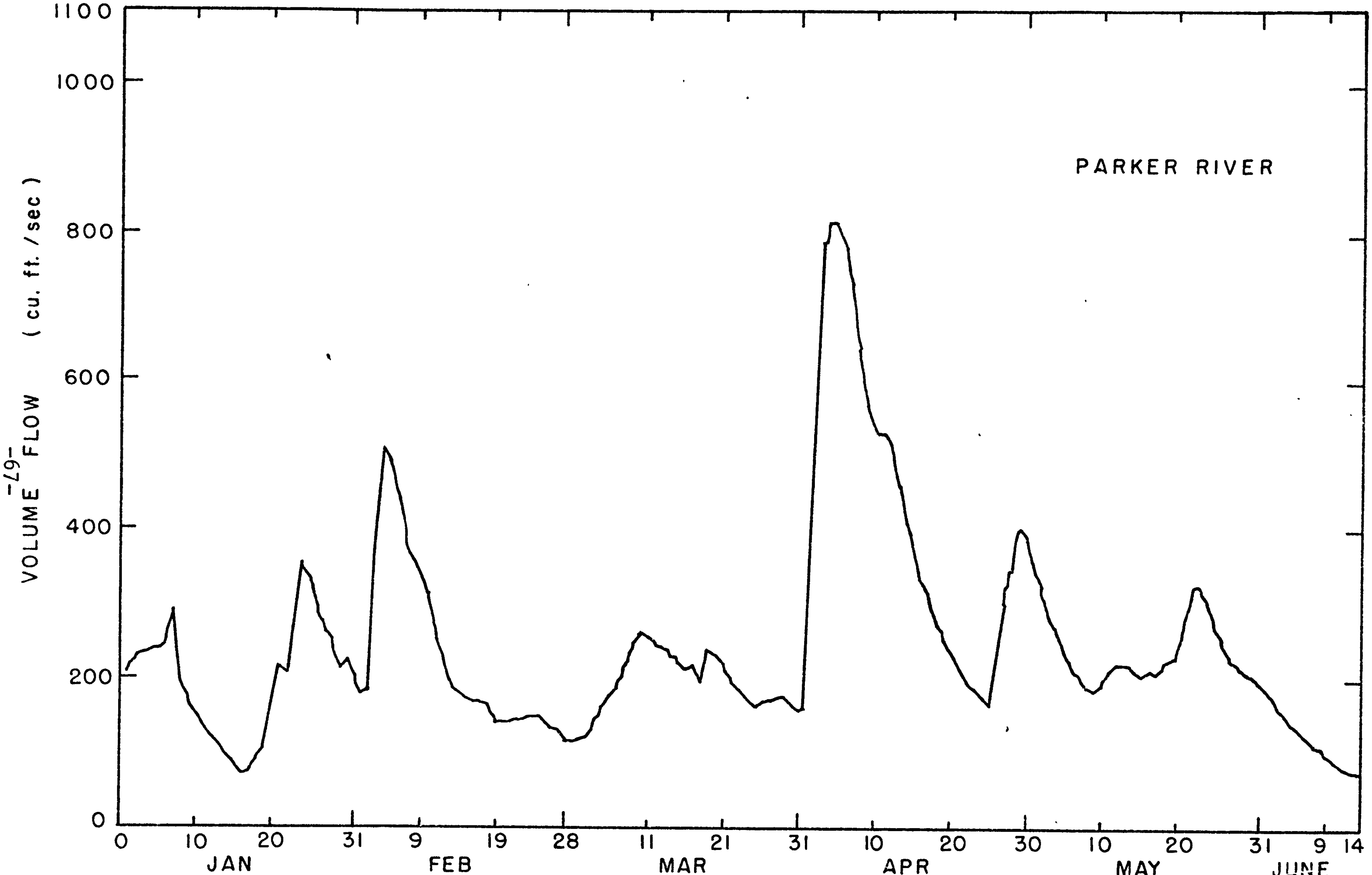


Figure 4.10: Daily Volume Flow of Parker River

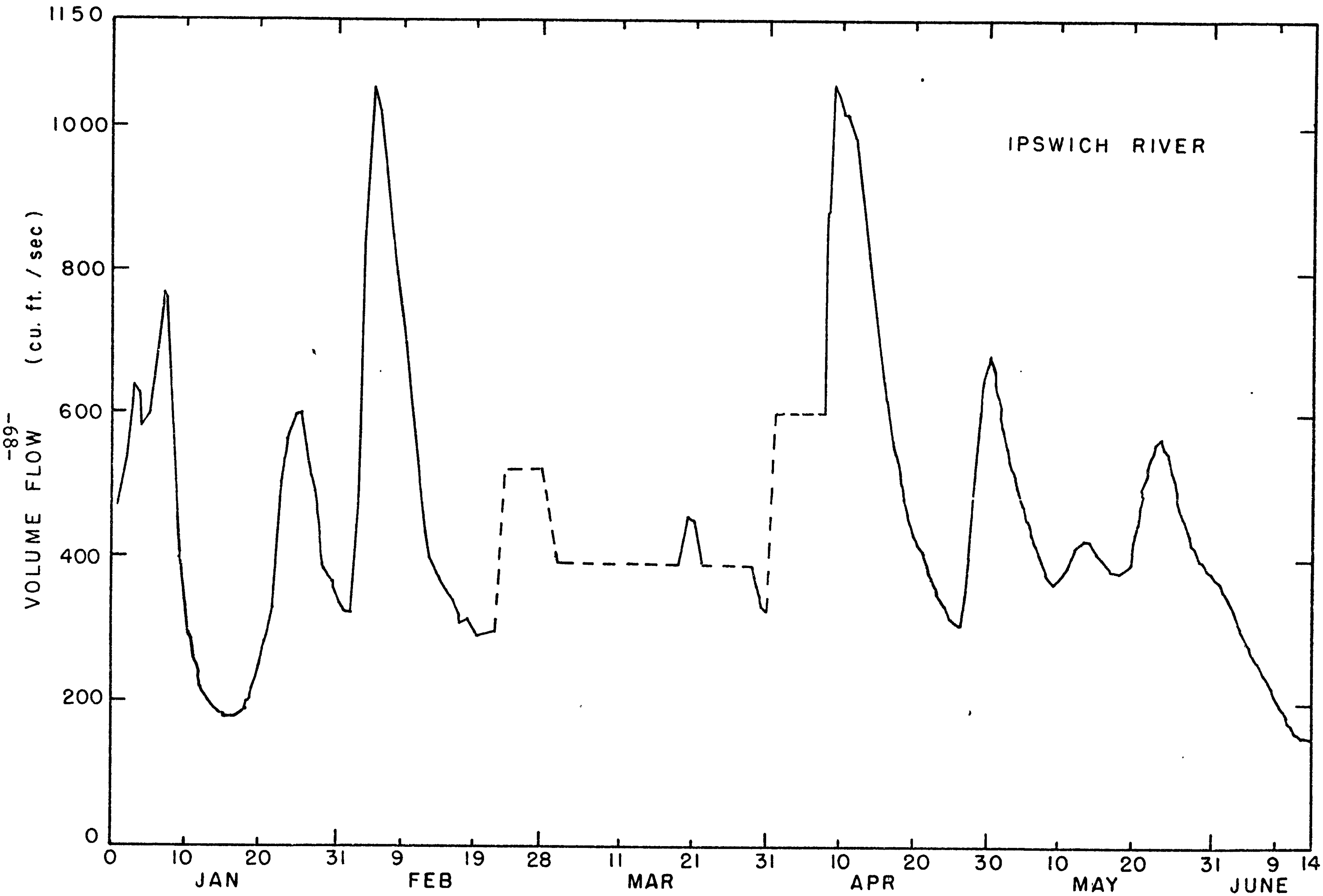


Figure 4.11 Daily Volume Flow of Ipswich River

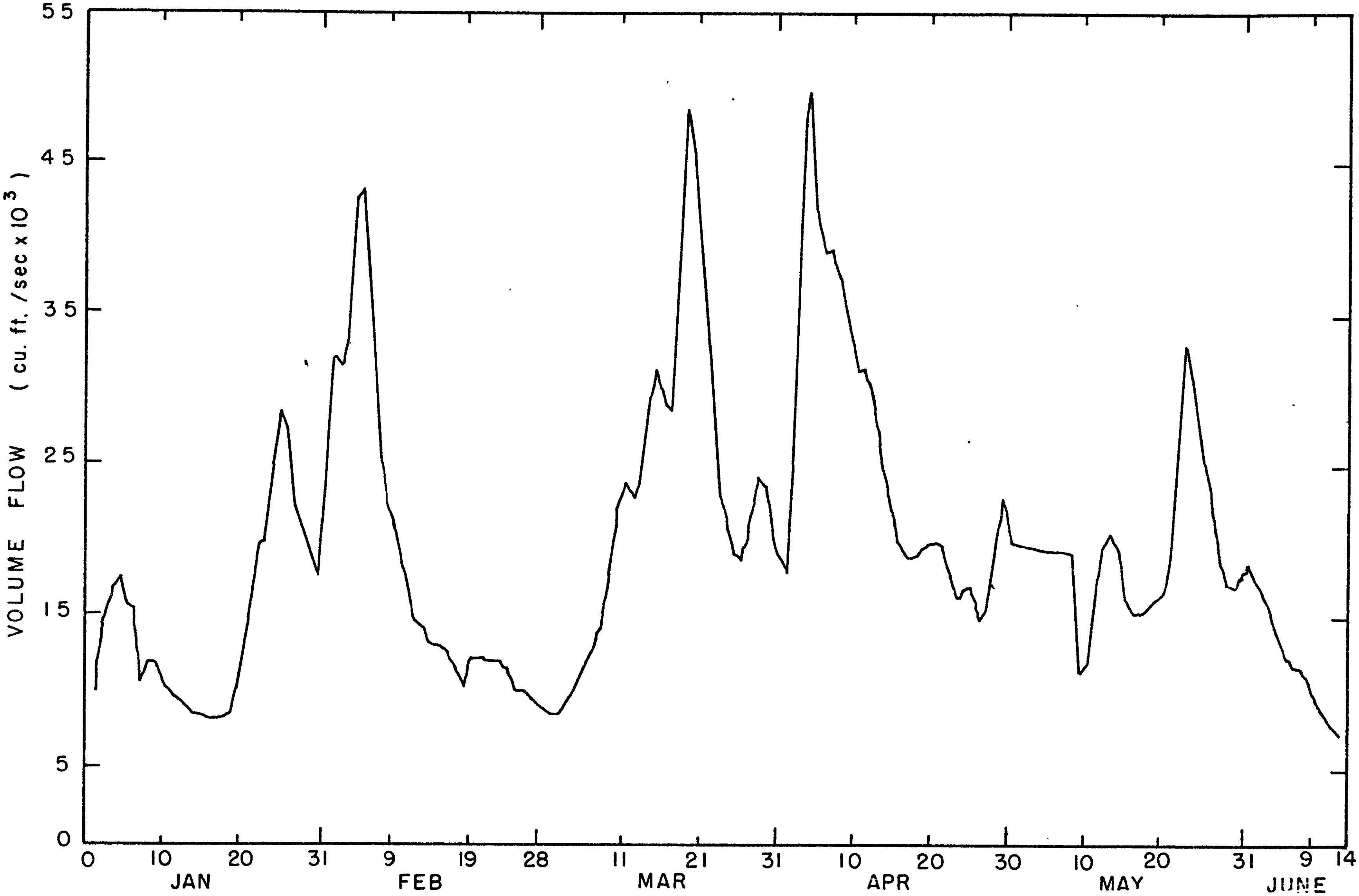


Figure 4.12: Total Daily Volume Flow of Fresh Water from Sources North of Cape Ann

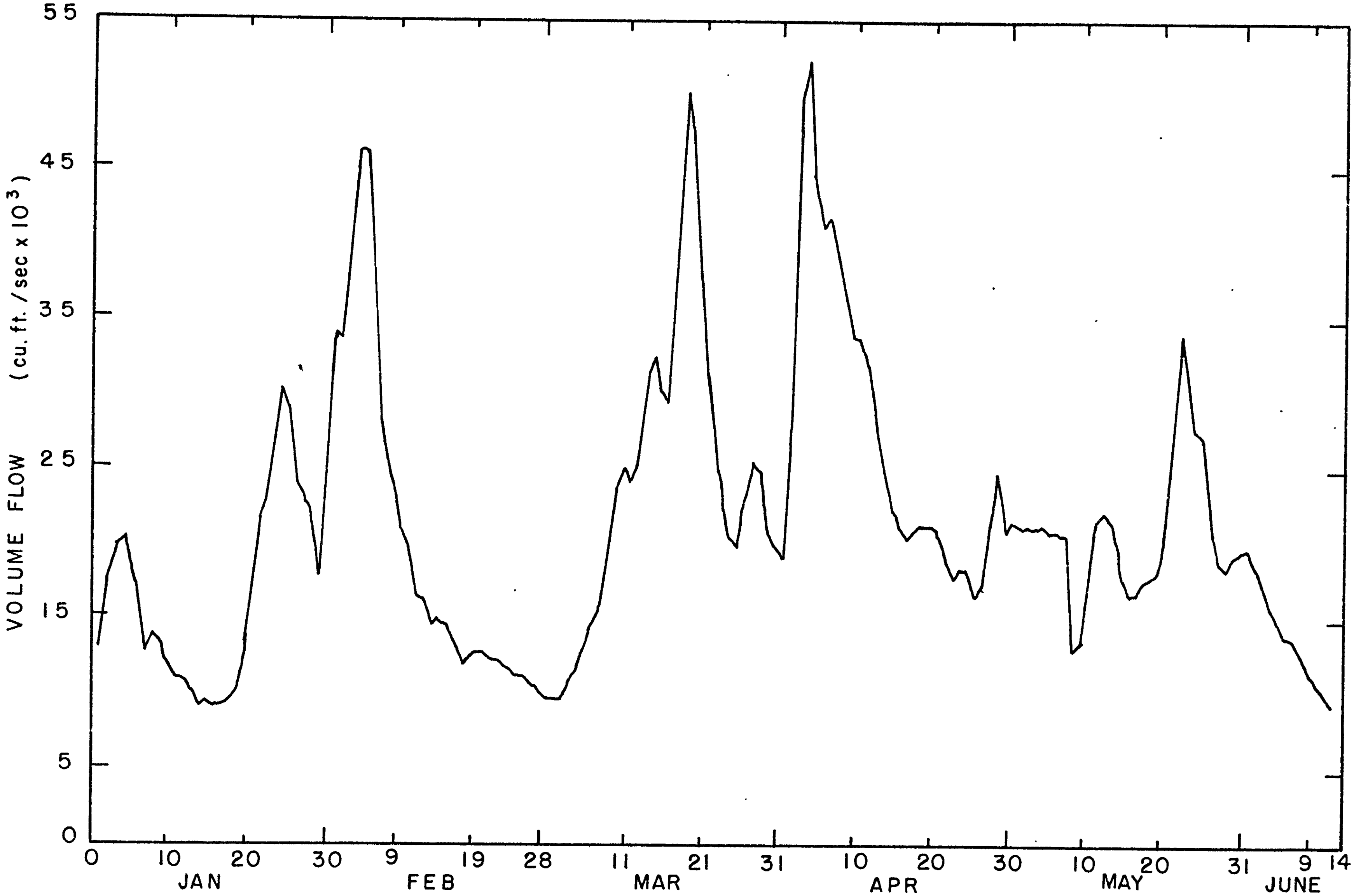


Figure 4.13: Total Daily Volume Flow of Fresh Water into Massachusetts Bay from All Sources

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A. Conclusions

The major source of fresh water in the Bay was seen to be the Merrimac, which accounts for about 90% of the total discharge during the spring months. This water comes into the Bay in the form of a tongue of low salinity water in the middle of the Bay, and slowly spreads out to encompass the Boston Lightship to the west and as far out as Stellwagen Bank to the east.

During the early spring the freshening effect of the run-off is felt most in the upper twenty meters, while in the late spring the bottom waters start getting fresh. The salinity difference from top to bottom is most marked during this period; this difference being almost 0 $^0/00$ during winter, and as great as 4.0 $^0/00$ by May.

For the spring of 1973, the maximum amount of fresh water in the Bay was 2,450 x 10^6 m^3 which occurred on May 25. This day, May 25, can then be said to mark the end of the vernal freshening of the Bay. There was quite a good correspondence between the volume of fresh water found in the Bay and the volume of fresh water that came in via the rivers; the discrepancy between these two figures being at no time greater than the error in the figure of the volume of fresh water in the Bay computed by the method of Ketchum and Keen (1955).

B. Future Work

The data collected for the region studied can be used to determine a much more accurate picture of the dynamics of the Bay. It would be possible also to trace the development of the thermocline from the winter to the spring.

No account was taken in this analysis of the effect of evaporation from and precipitation onto the Bay. There is little data available to determine the amount of evaporation that takes place in the Bay, and this is one region where some work can be concentrated in the future. The tacit assumption used in determining the volume of fresh water in the Bay is that the effect of evaporation from the Bay is cancelled by the effect of direct precipitation on the Bay. Although previous estimates of these factors, Craig and Montgomery (1949), show this to be a reasonable assumption, the data used was very scanty and it should be verified by further work.

APPENDIX A

```
C      THIS SUBROUTINE CALCULATES SALINITY
C      BASED ON THE COX, CULKIN, AND RILEY DATA
       SUBROUTINE SALIN(T,P,C,S)
        DOUBLE PRECISION RT
        S = 35.00
       T1 = T
        T2 = T1 * T1
        T3 = T2 * T1
        T4 = T3 * T1
        TD = T1 - 15.0
       P1 = P
        P2 = P1 * P1
        P3 = P2 * P1
        G = 1.5192 - 4.5302E-2 * T1 + 8.3089E-4 * T2 - 7.9E-6 * T3
        F = 1.042E-3 * P1 - 3.3913E-8 * P2 + 3.3E-13 * P3
        H = 4.0E-4 + 2.577E-5 * P1 - 2.492E-9 * P2
        AJ = 1.0 - 1.535E-1 * T1 + 8.276E-3 * T2 - 1.657E-4 * T3
        AL = 6.95E-3 - 7.6E-5 * T1
        SP = G * F + H * AJ
        RC = C / 42.909
        RT = 0.067652453D1 + 0.20131661D-1 * T1 + 0.99886585D-4 * T2
     1       - 0.19426015D-6 * T3 - 0.67249142D-8 * T4
  210 S0 = S
        AM = 35.0 - S
        RP = 1.0 + (1.0 + AL * AM) * SP * 1.0E-2
       RS=RC/(RT*RP)
        RS2 = RS * RS
        R15 = RS + 1.0E-5 * RS * (RS - 1.0) * TD * (96.7 - 72.0 * RS
     1    + 37.3 * RS2 - (0.63 + 0.21 * RS2) * TD)
        R152 = R15 * R15
        R153 = R152 * R15
        R154 = R153 * R15
        R155 = R154 * R15
        S = -0.08996 + 28.2972 * R15 + 12.80832 * R152 - 10.67869 * R153
     1    + 5.98624 * R154 - 1.32311 * R155
       IF (ABS(S-S0) -0.001) 220,210,210
  220 RETURN
        END
```

APPENDIX B

CALIBRATION CURVES FOR INSTRUMENTS USED

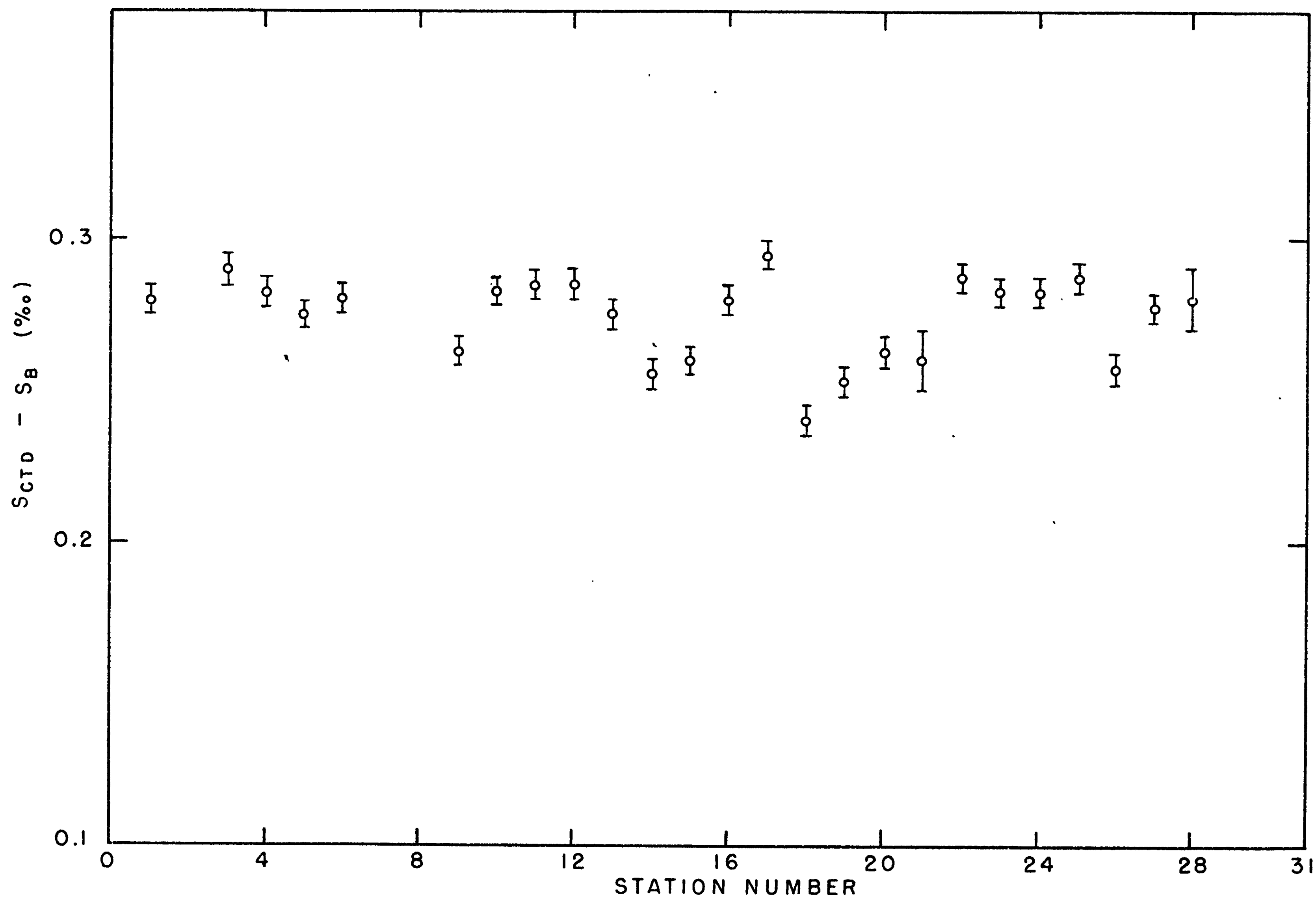


Figure 1: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 29-30 March

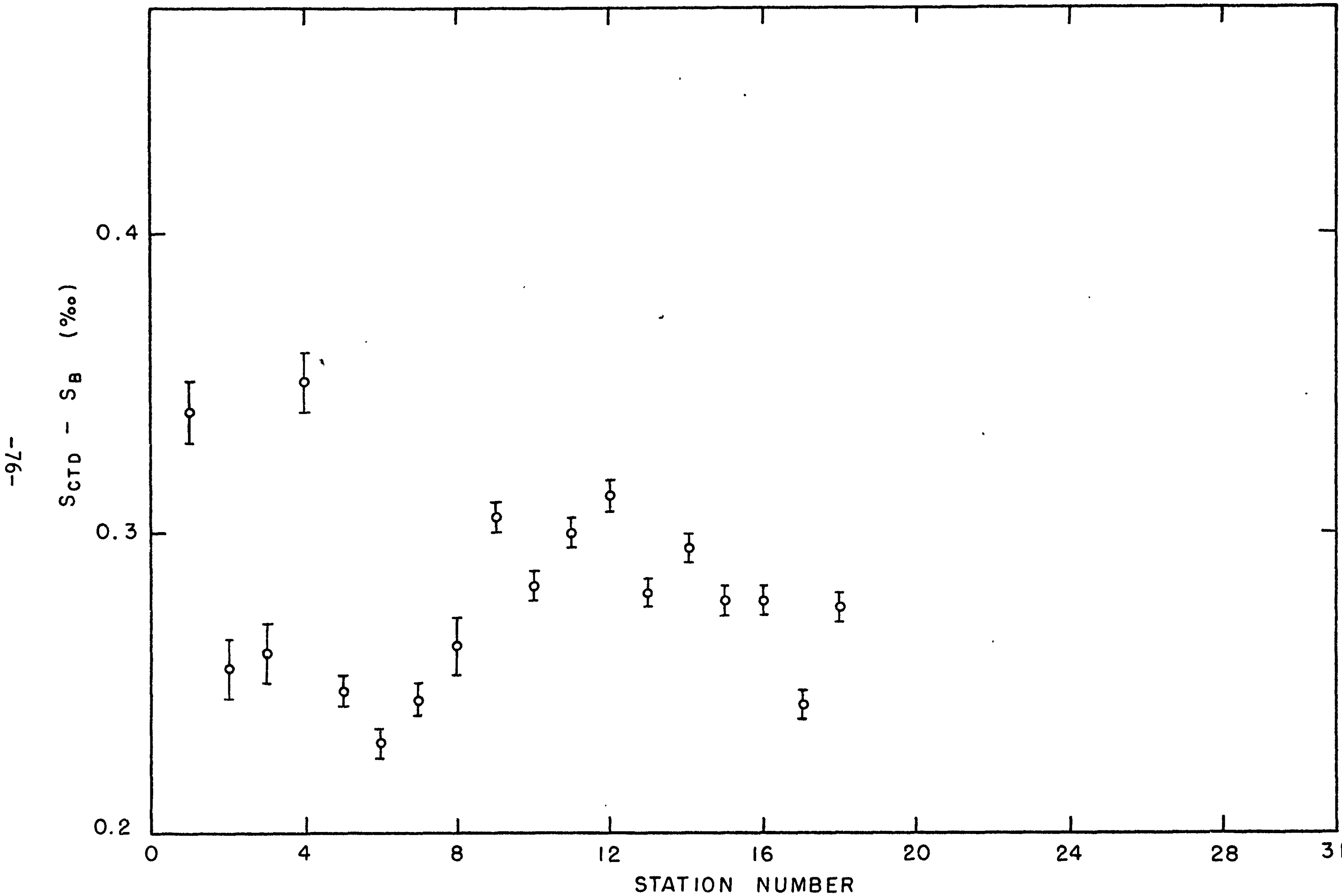


Figure 2: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 14-15 April

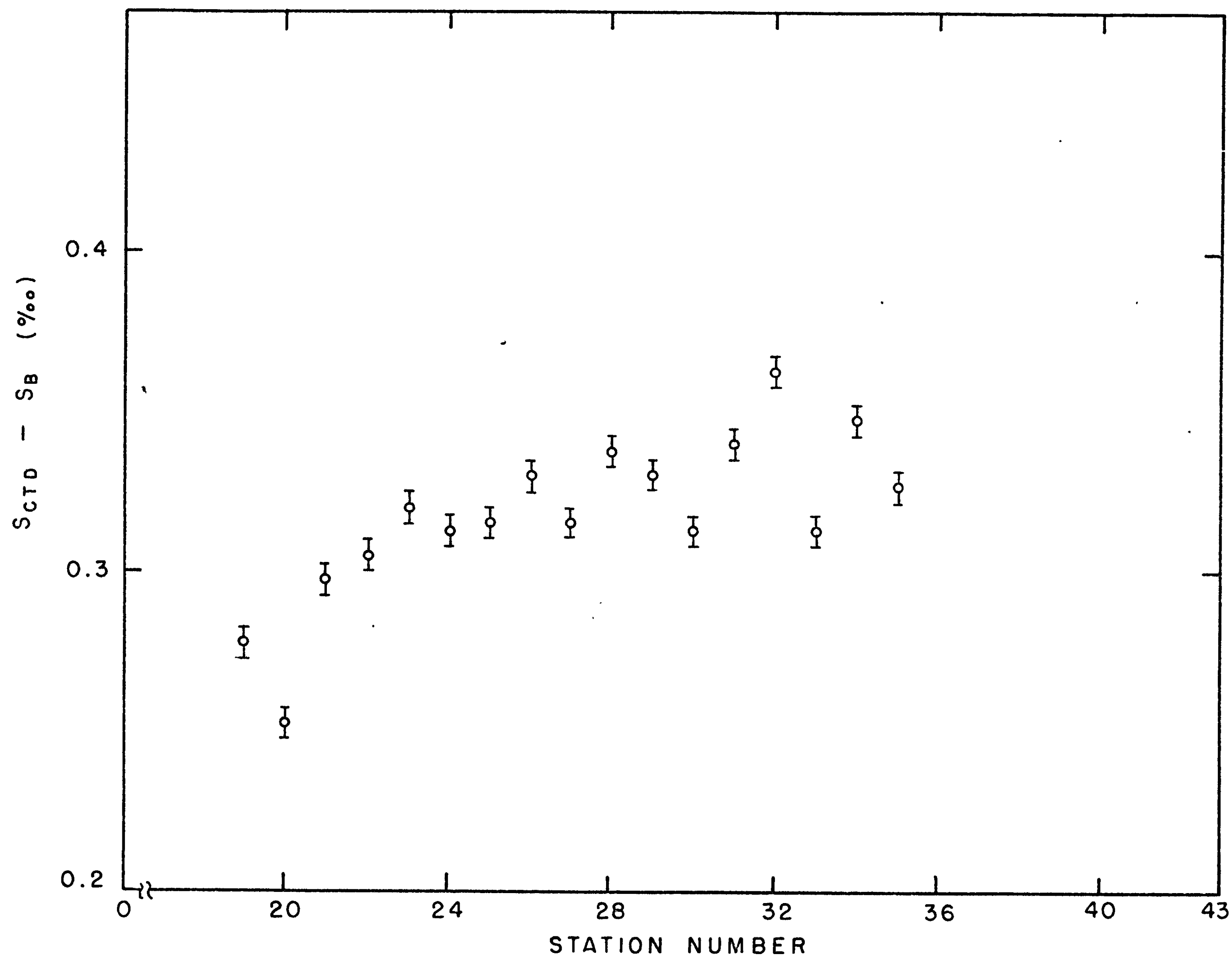


Figure 3: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 21-22 April

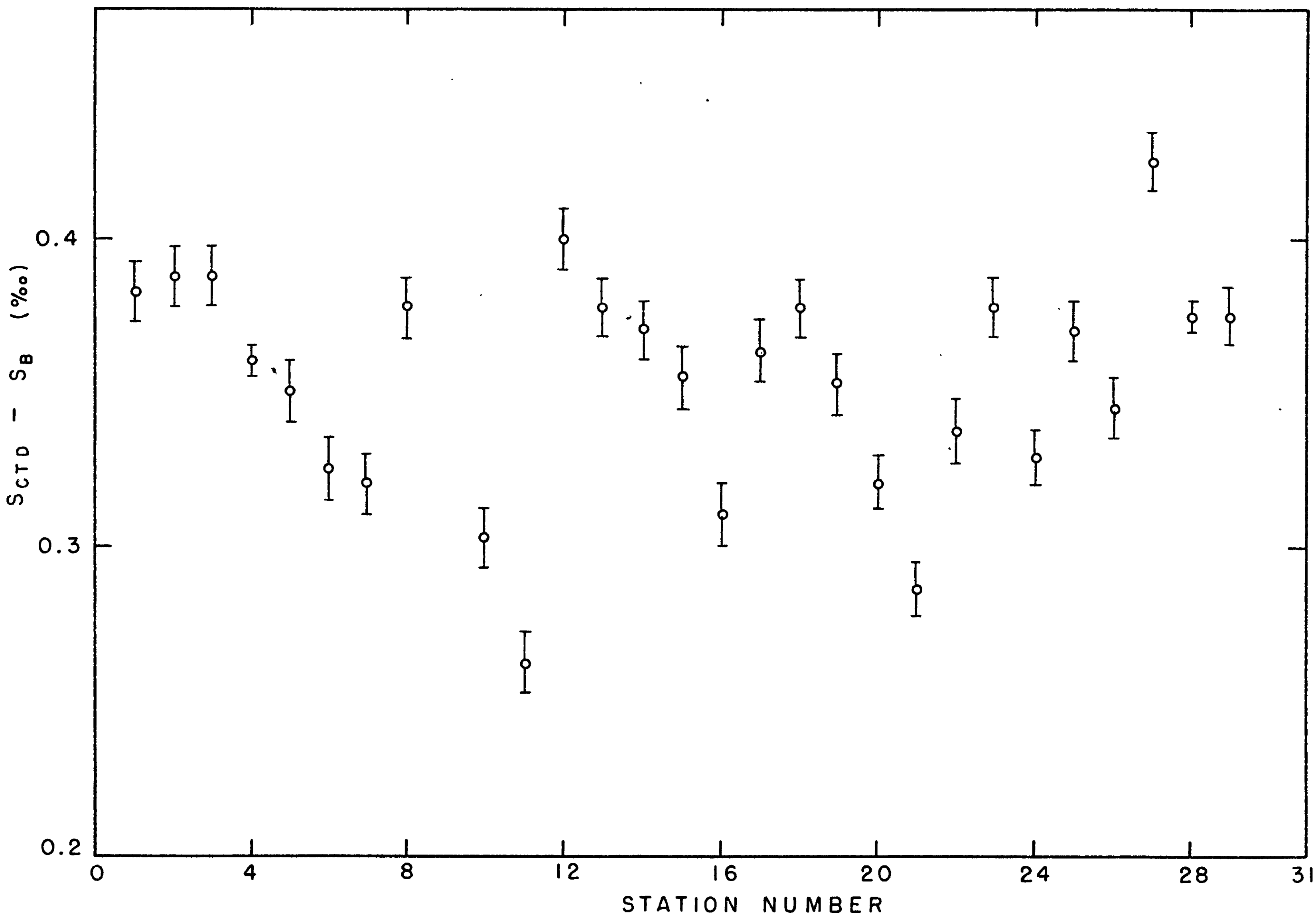


Figure 4: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 5-6 May

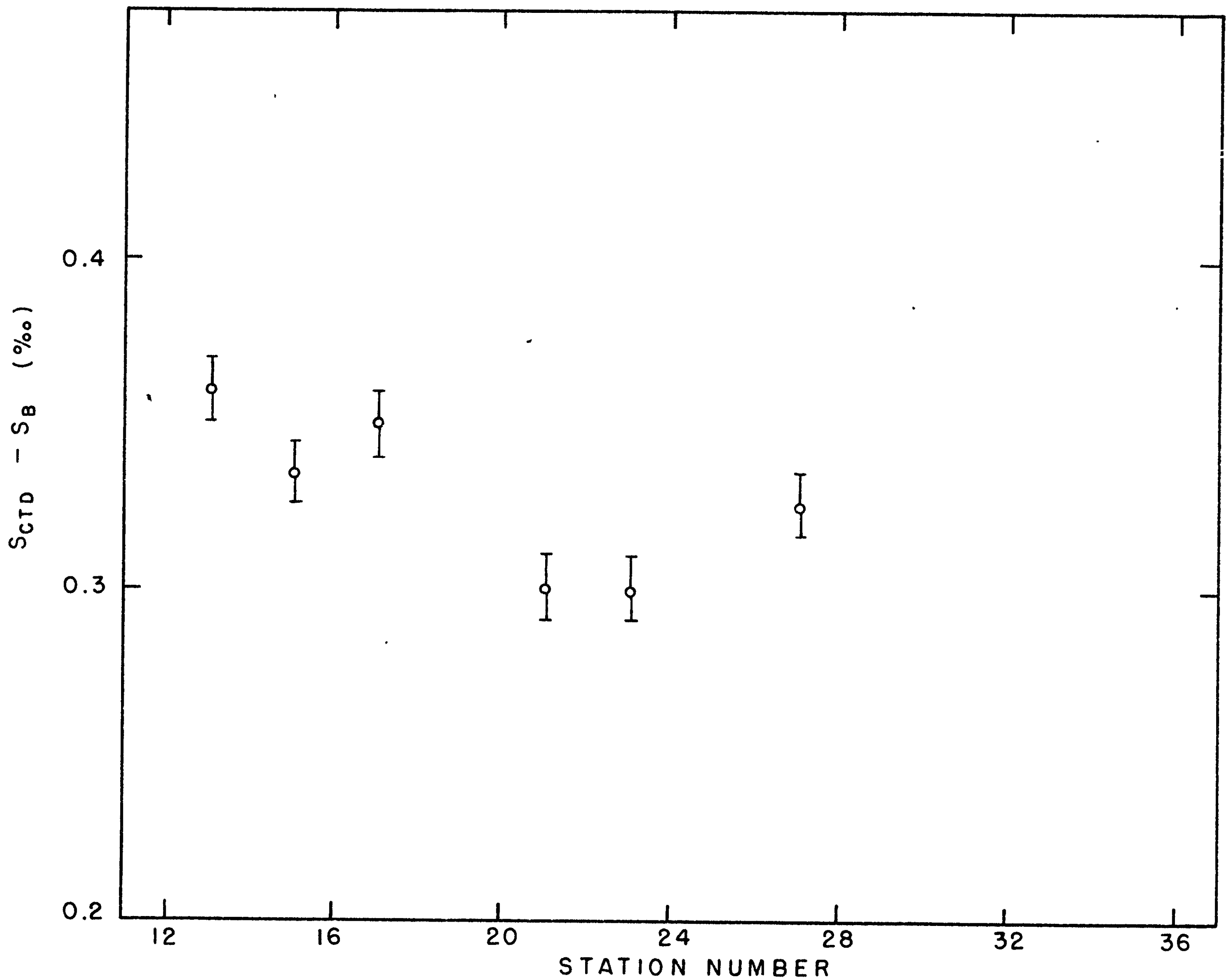


Figure 5: Difference of C.T.D. Reading from Bottle Reading (Bottom) vs Station Number. 5-6 May

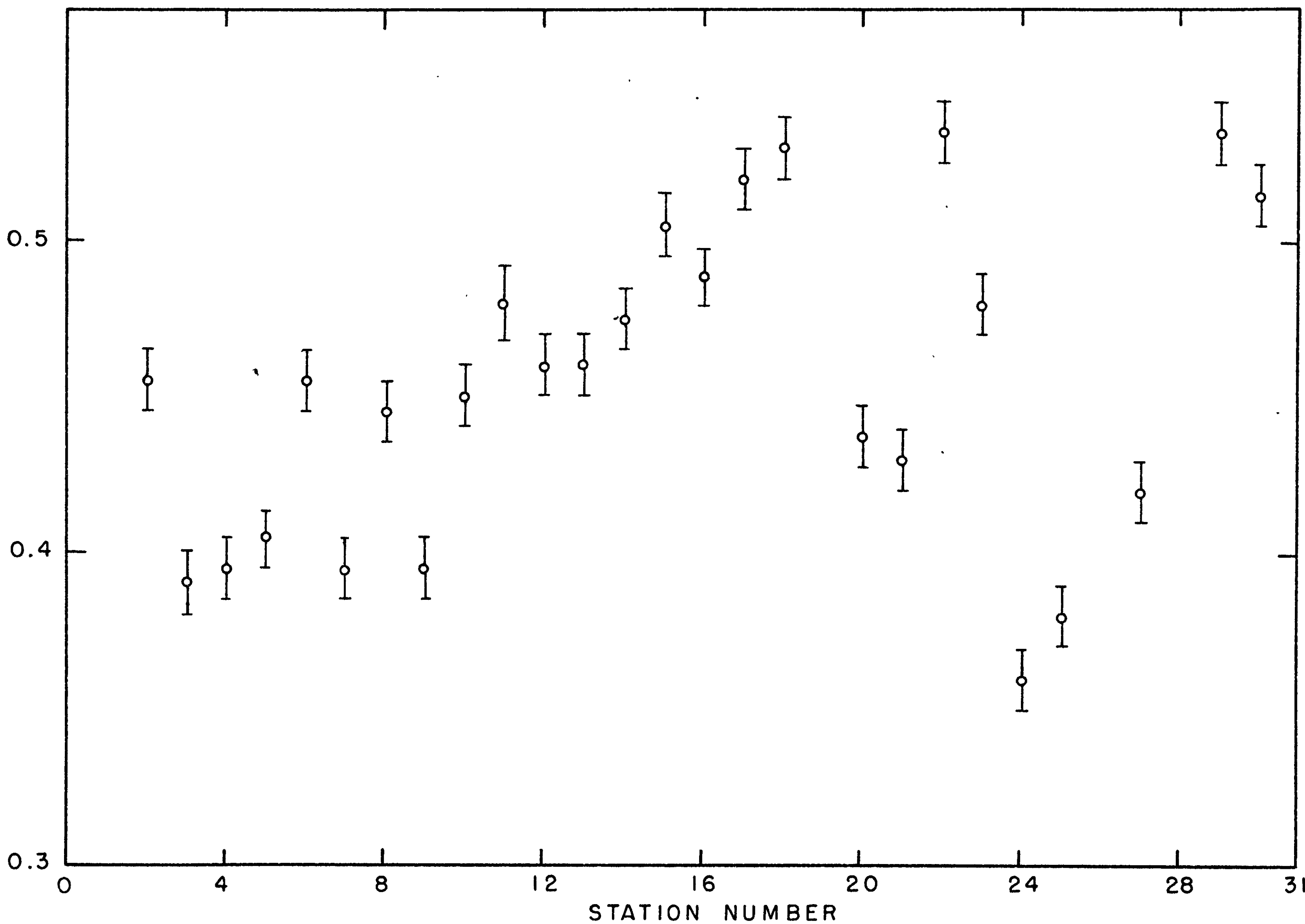


Figure 6: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 2-3 June

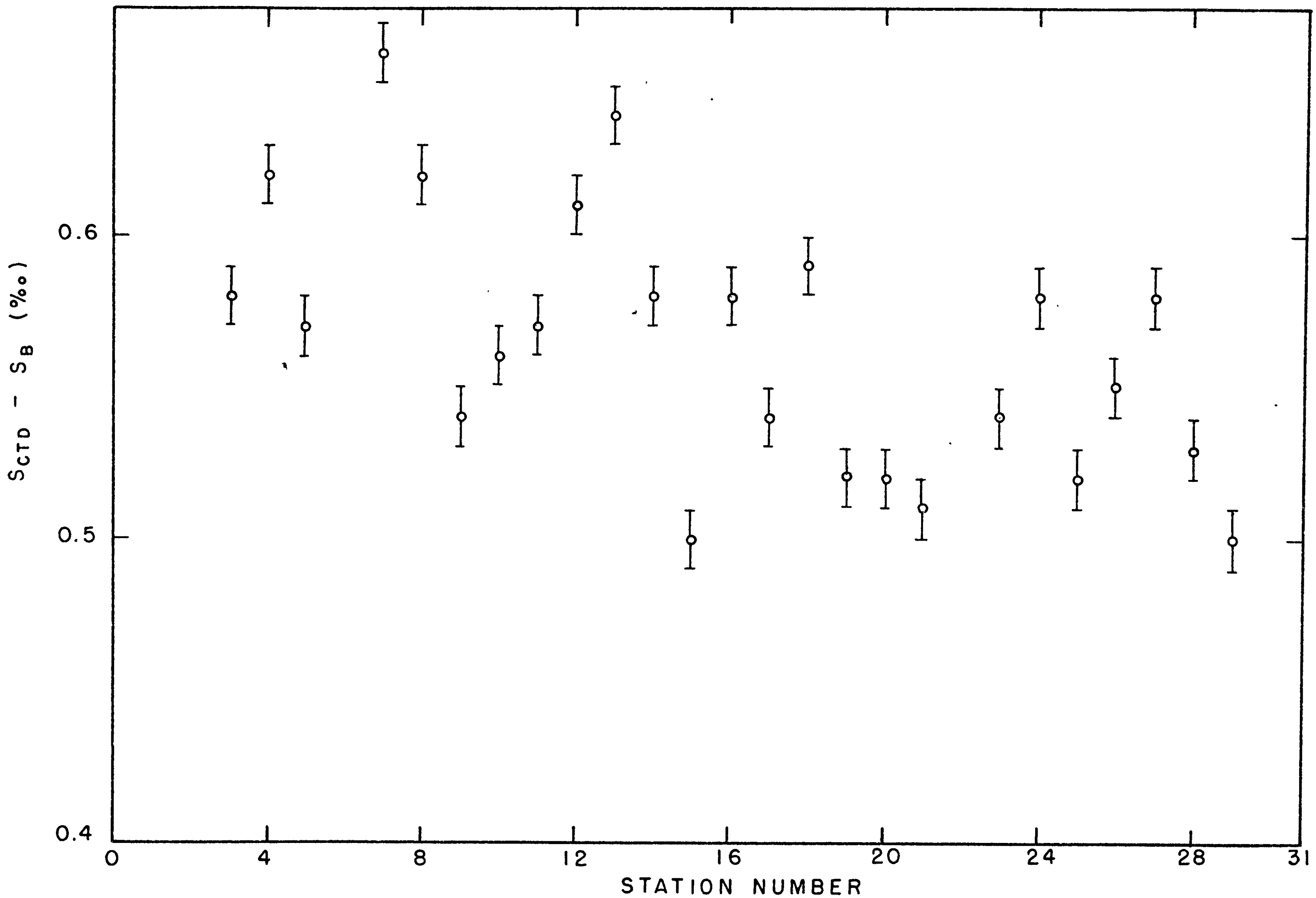


Figure 7: Difference of C.T.D. Reading from Bottle Reading vs Station Number. 13-14 June

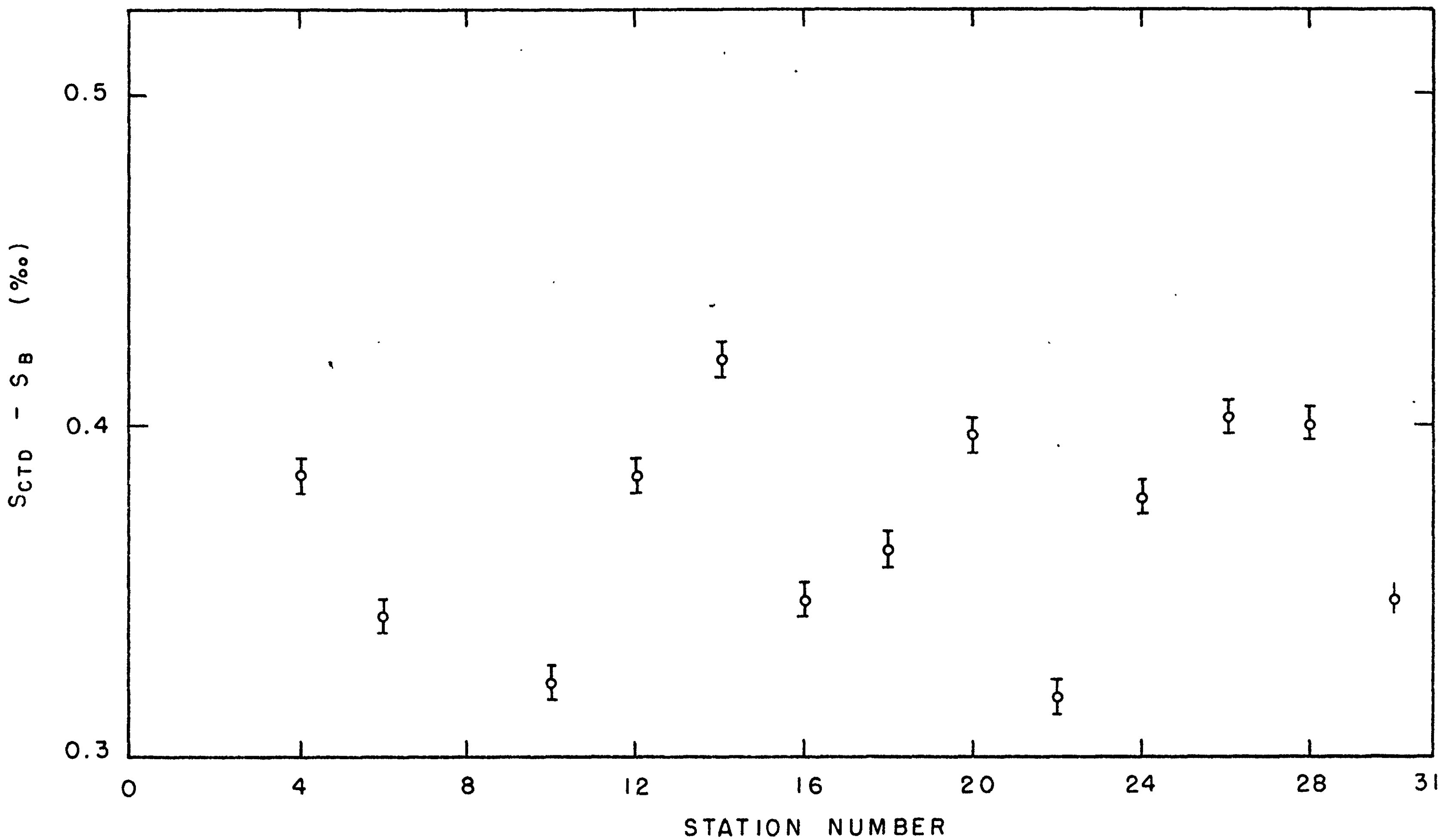


Figure 8: Difference of C.T.D. Reading from Bottle Reading (Bottom) vs Station Number. 13-14 June

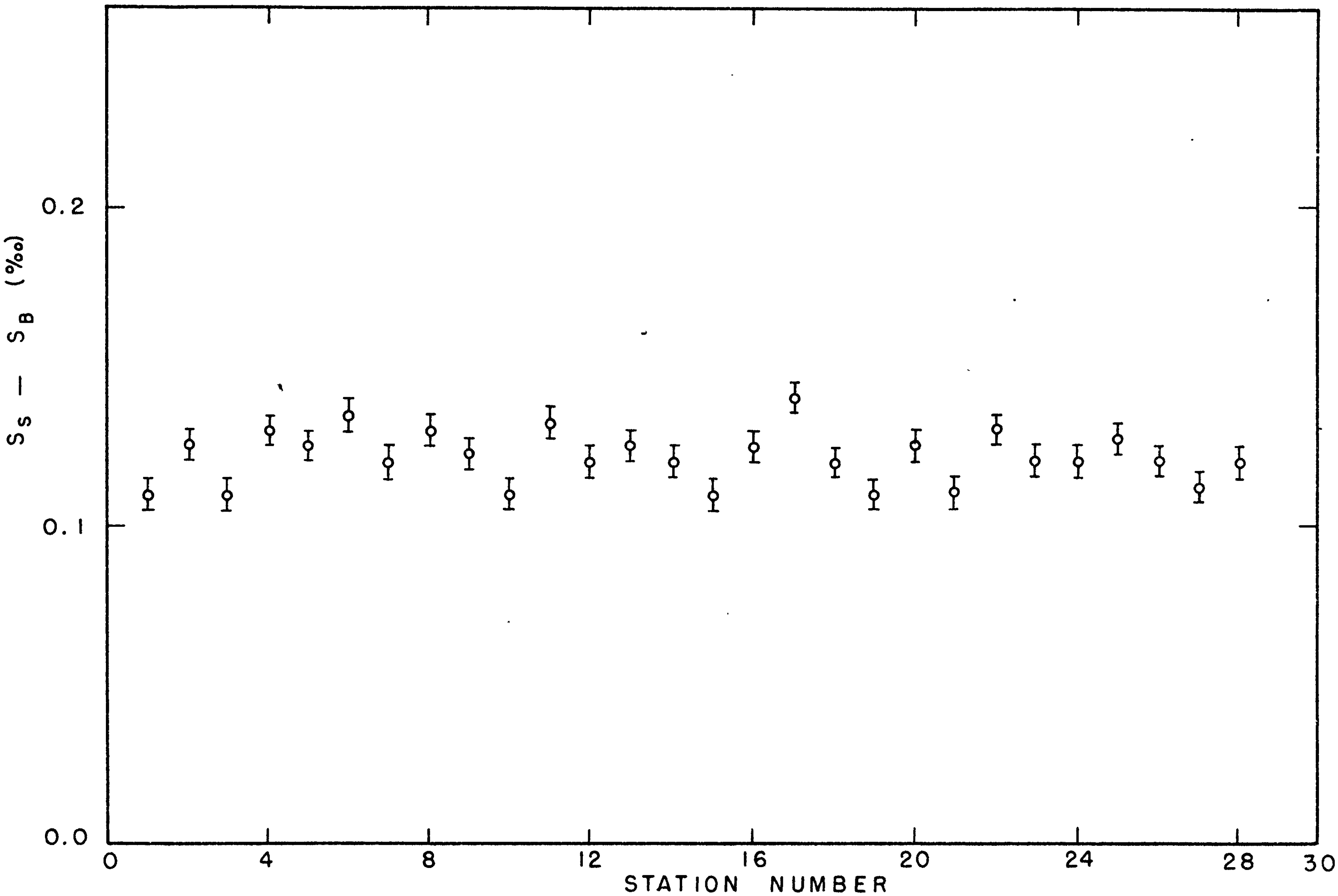


Figure 9: Difference of Salinograph Reading from Bottle Reading vs Station Number. 29-30 March

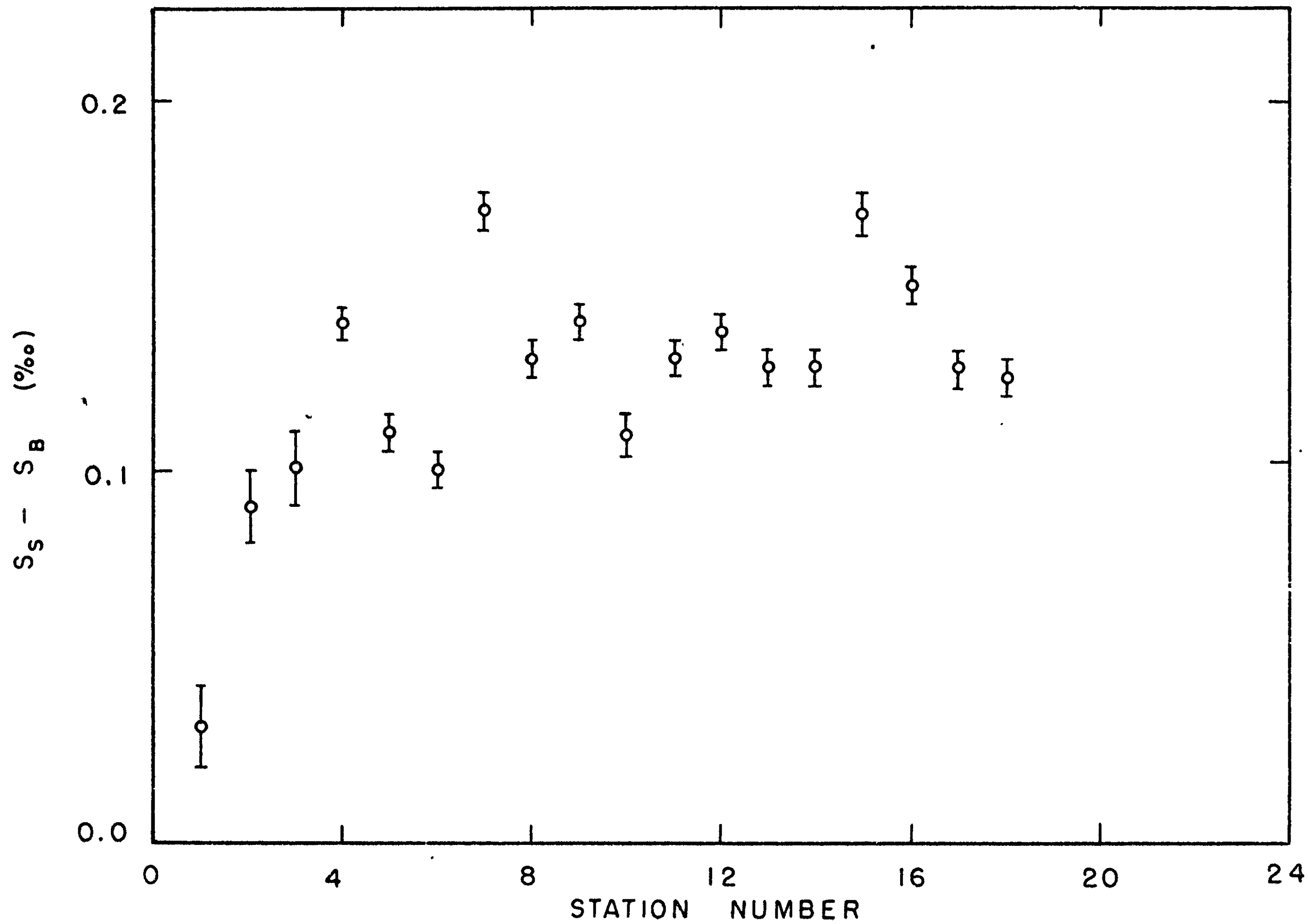


Figure 10: Difference of Salinograph Reading from Bottle Reading vs Station Number 14-15 April

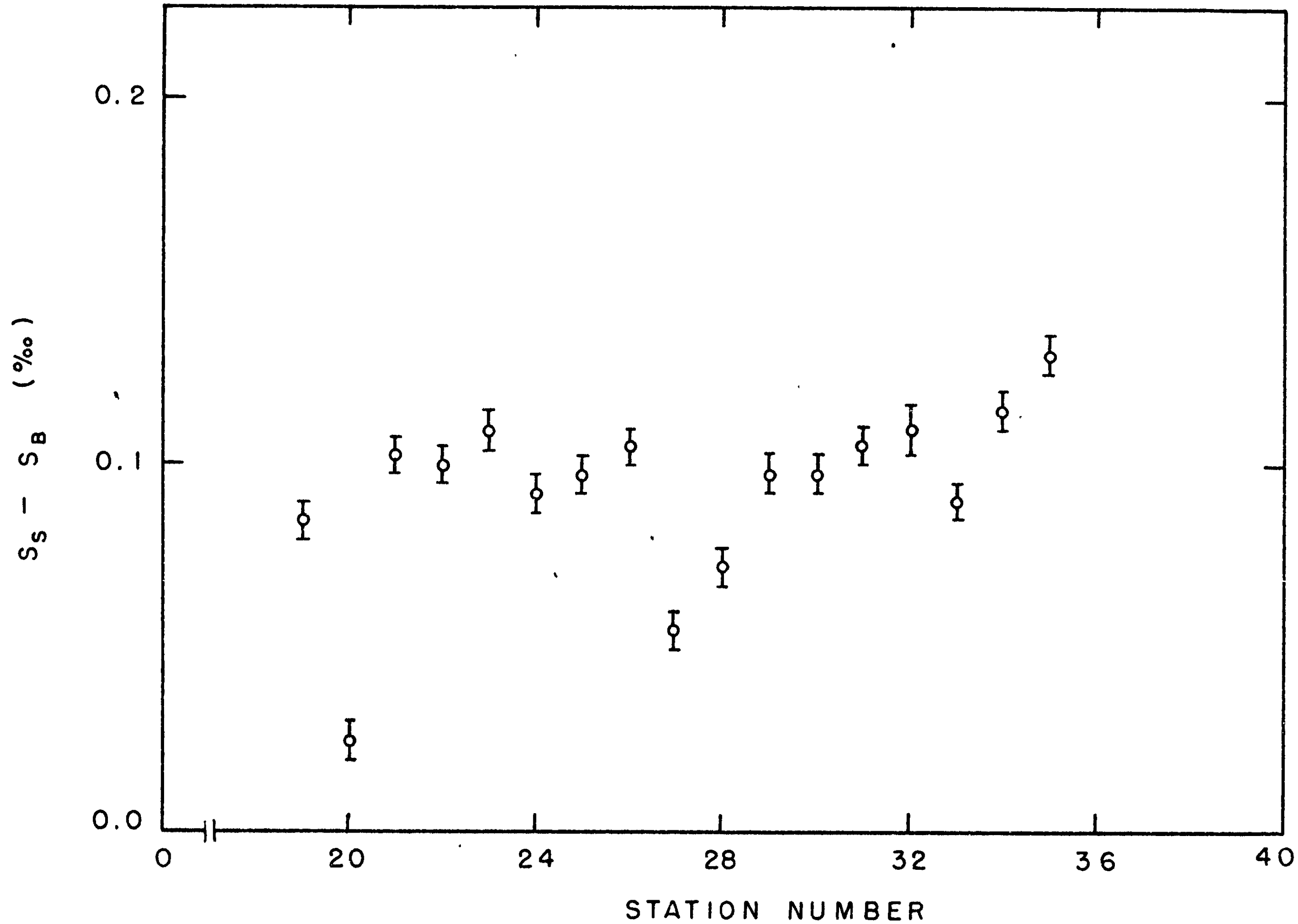


Figure 11: Difference of Salinograph Reading from Bottle Reading vs Station Number
21-22 April

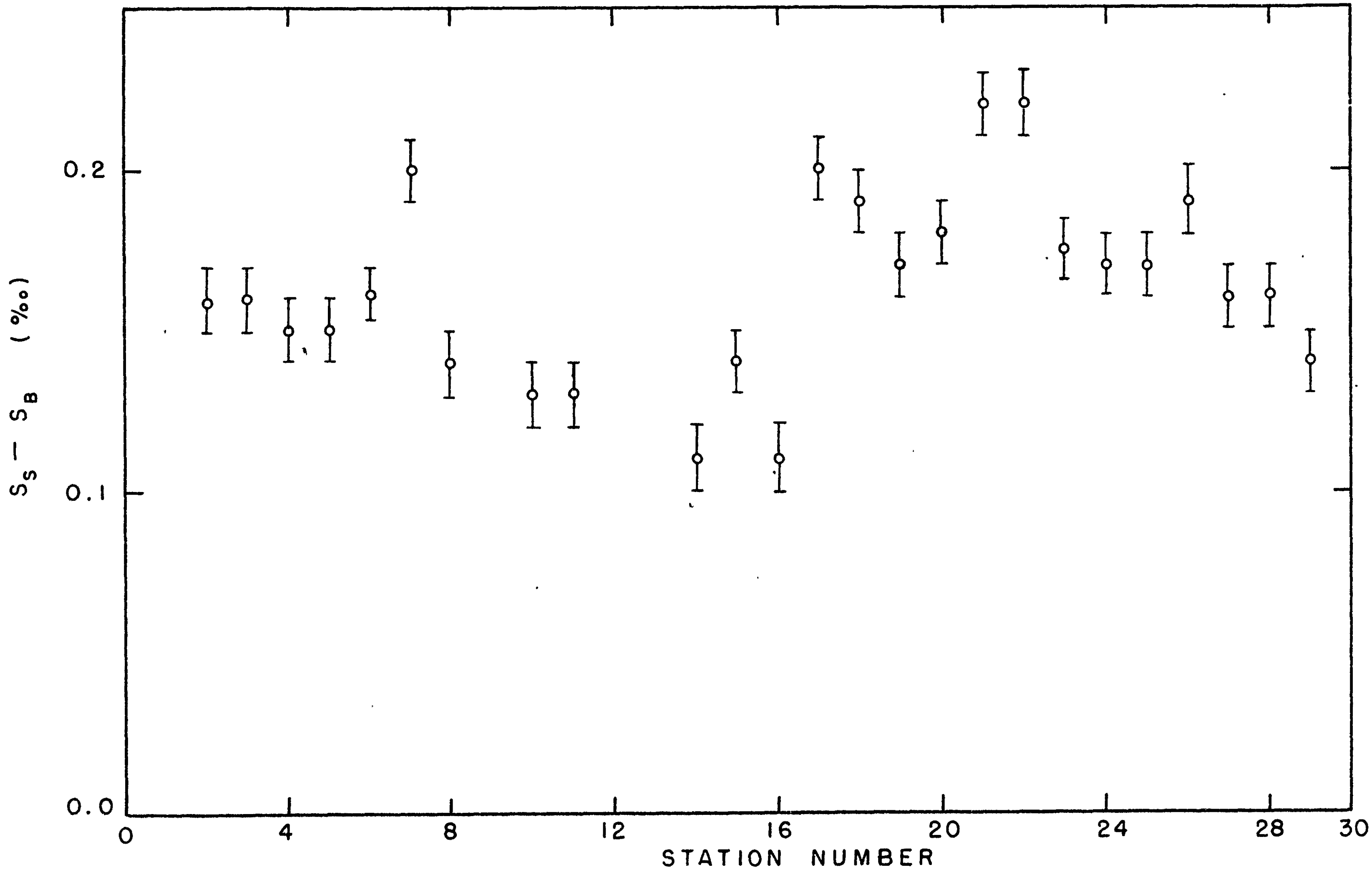


Figure 12: Difference of Salinograph Reading from Bottle Reading vs Station Number. 5-6 May

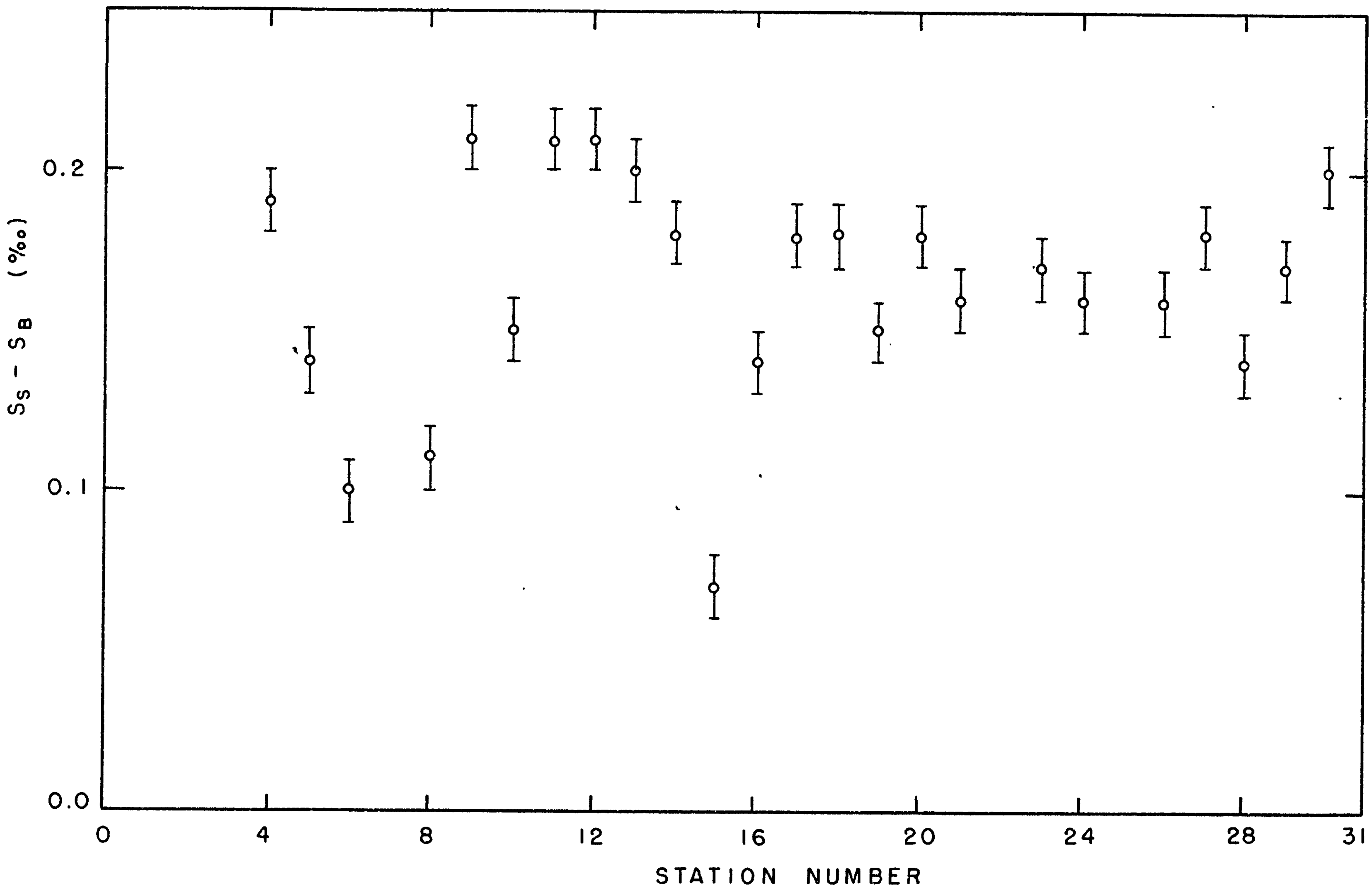


Figure 13: Difference of Salinograph Reading from Bottle Reading vs Station Number. 13-14 June

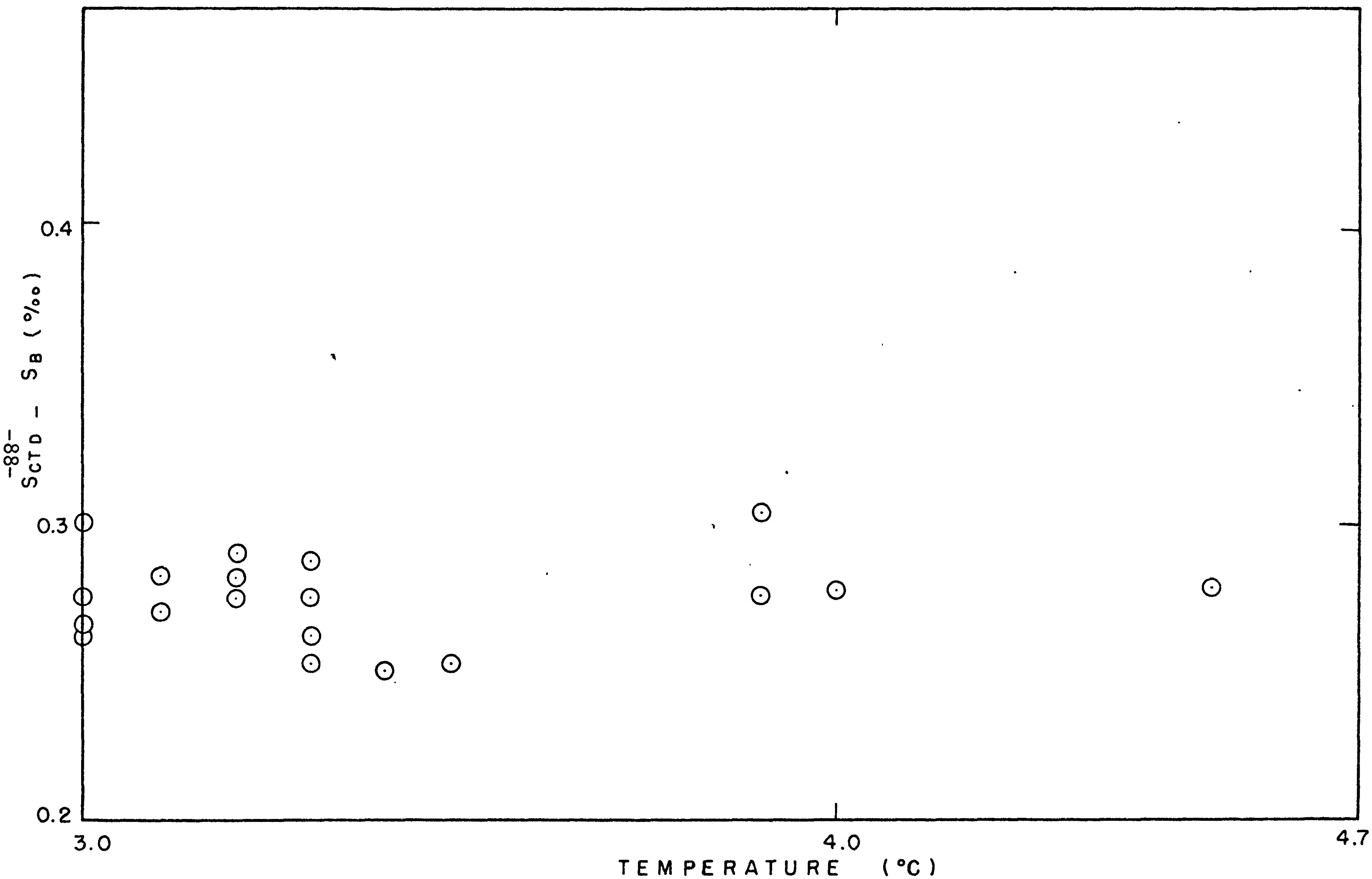


Figure 14: Difference of C.T.D. Reading from Bottle Reading vs in situ Temperature. 29-30 March

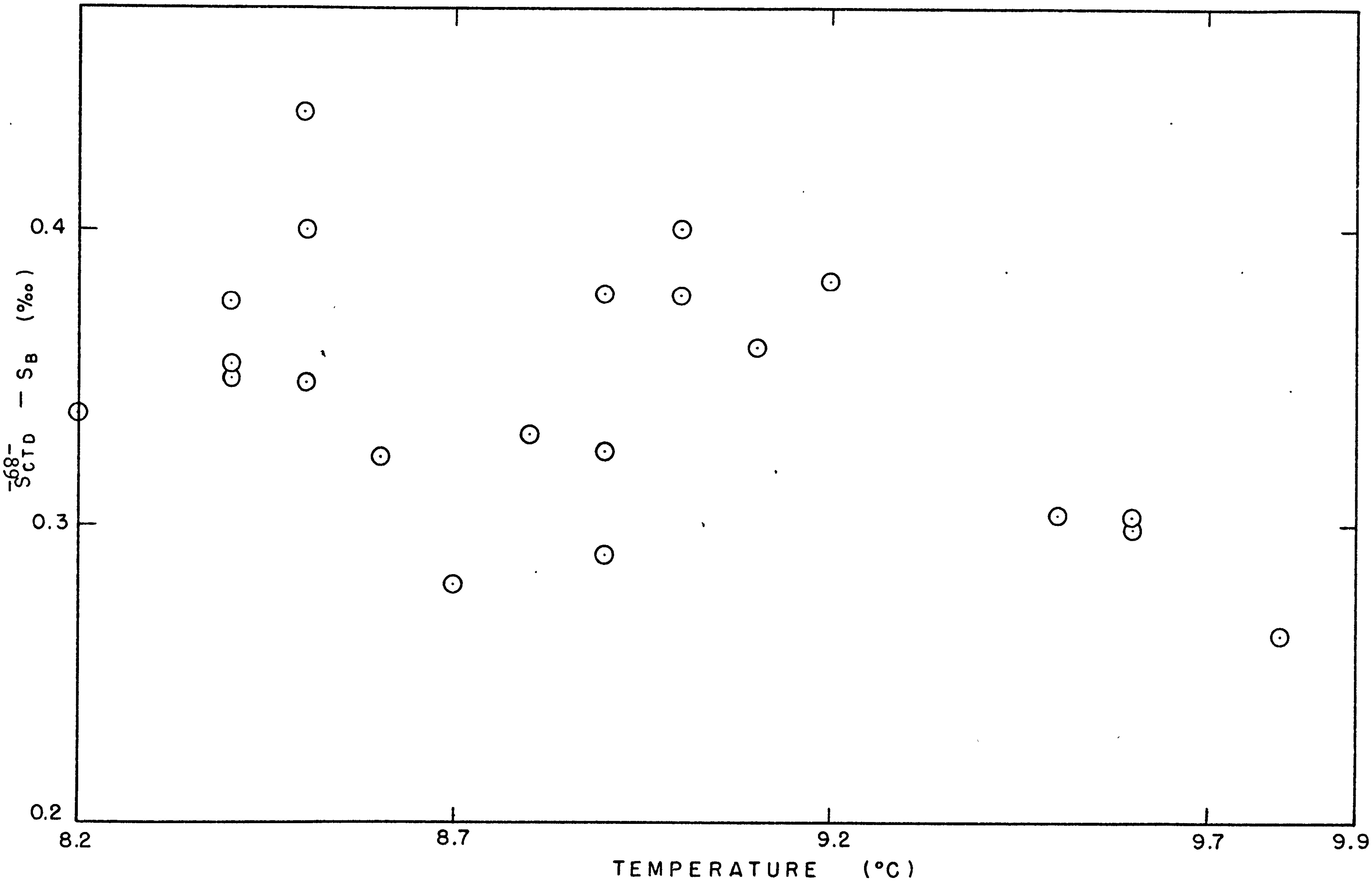


Figure 15: Difference of C.T.D. Reading from Bottle Reading vs in situ Temperature. 5-6 May

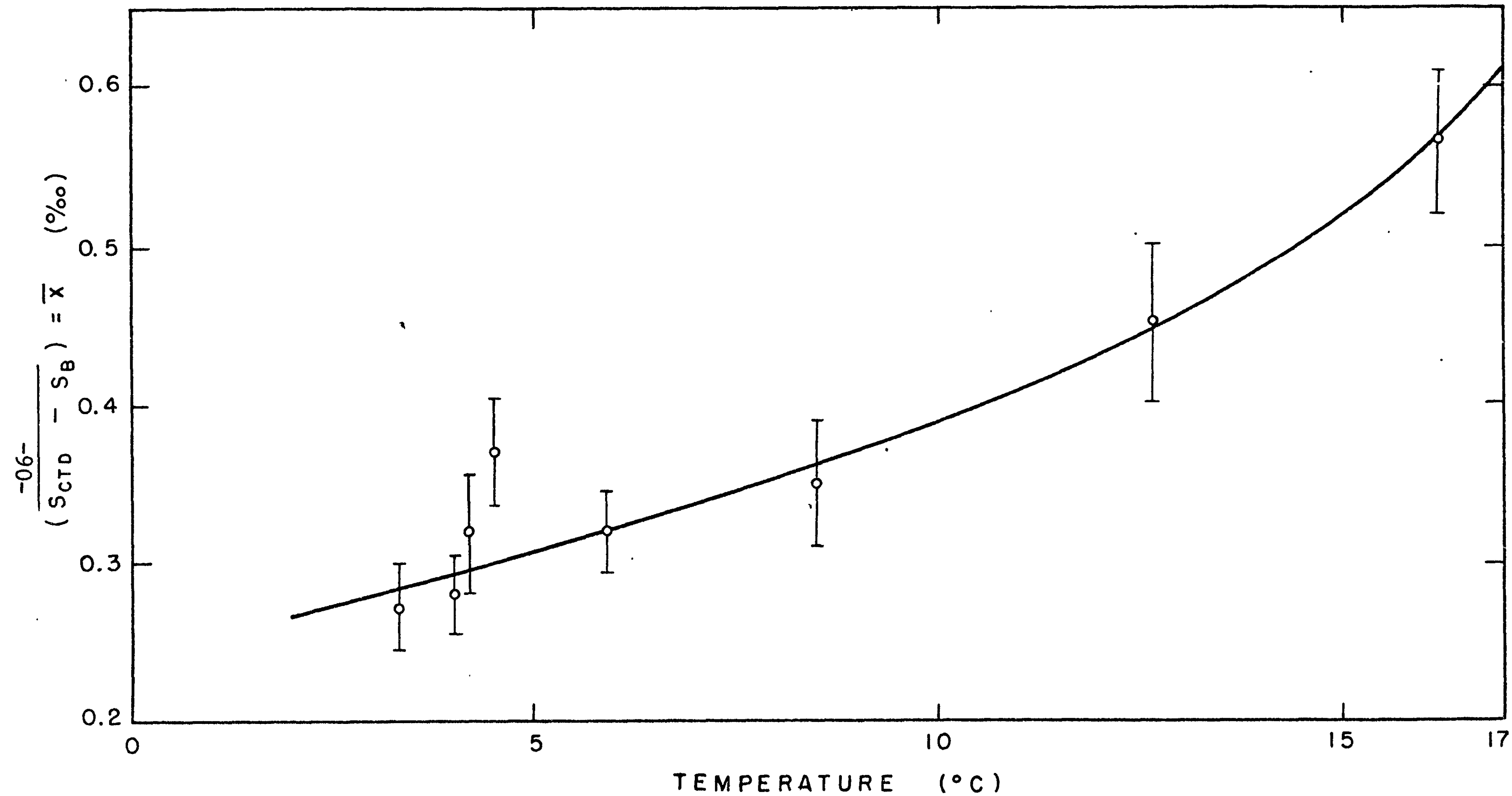


Figure 16: Mean Deviation of C.T.D. Reading from Bottle Reading vs Mean in situ Temperature

APPENDIX C

VERTICAL PROFILE OF SALINITY AND
TEMPERATURE AT STATIONS 17, 11, 16 and 18

29-30 MARCH 1973

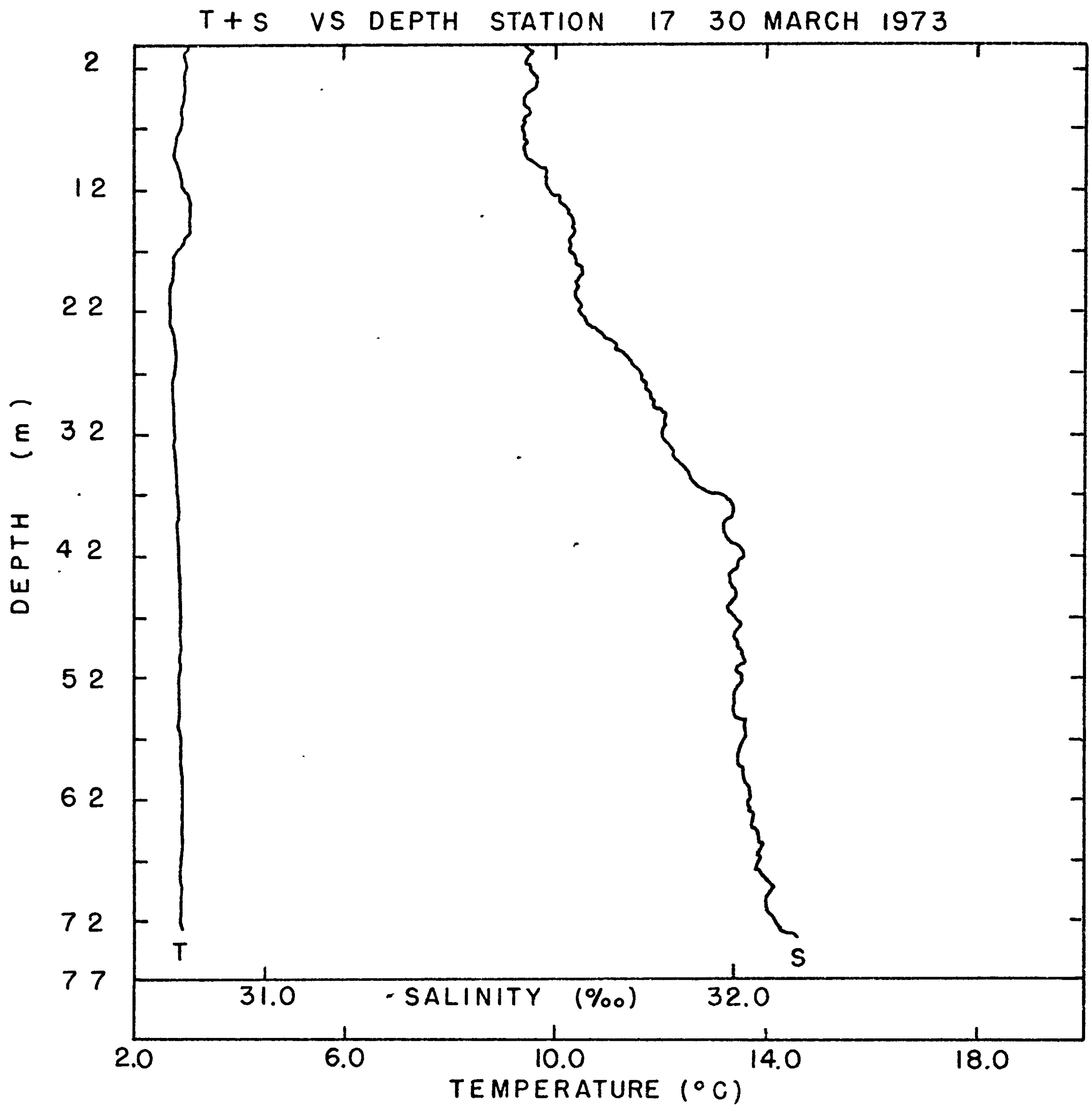


Figure 1: Salinity and Temperature vs Depth at Station 17, 29-30 March

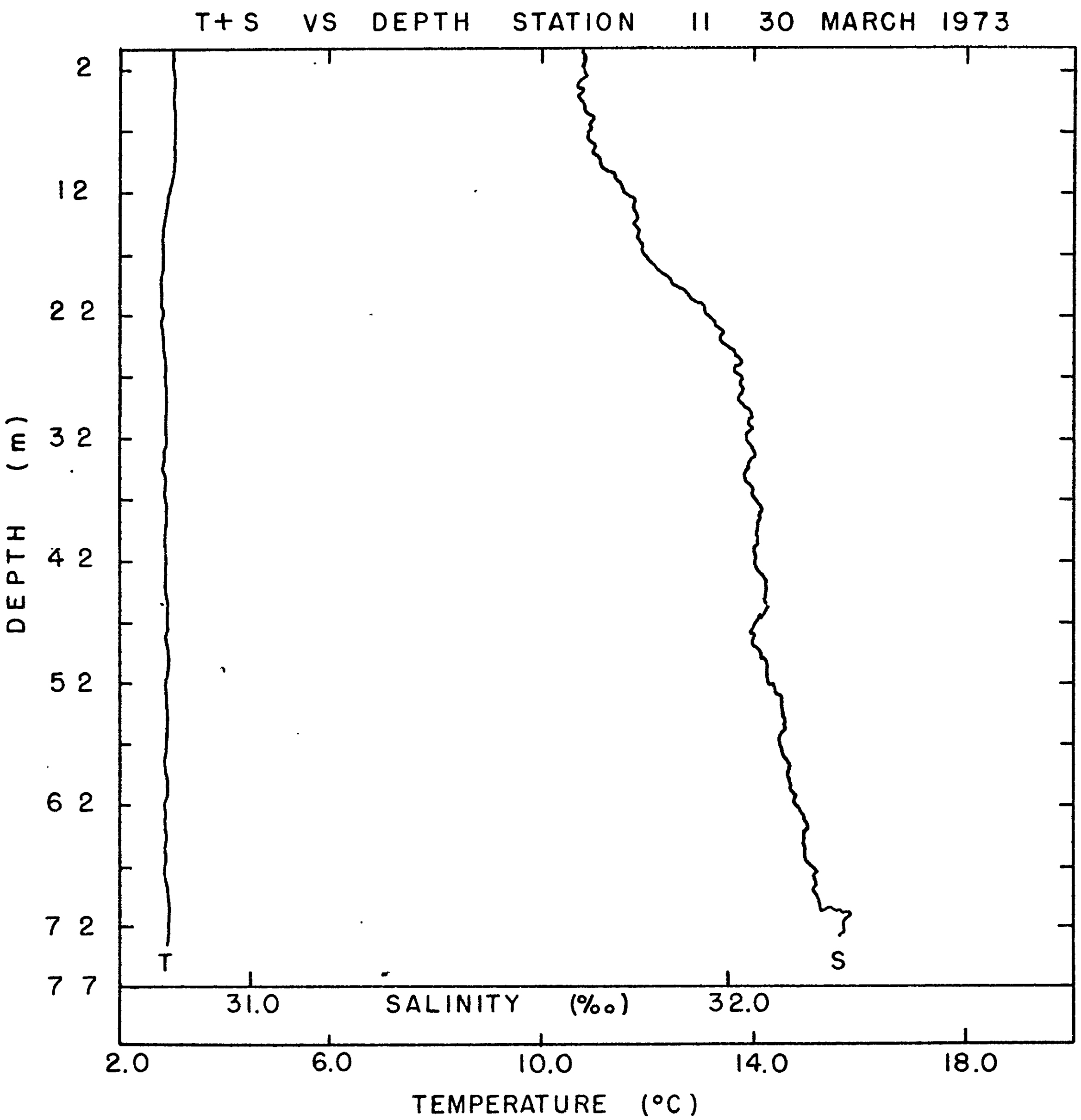


Figure 2: Salinity and Temperature vs Depth at Station 11, 29-30 March

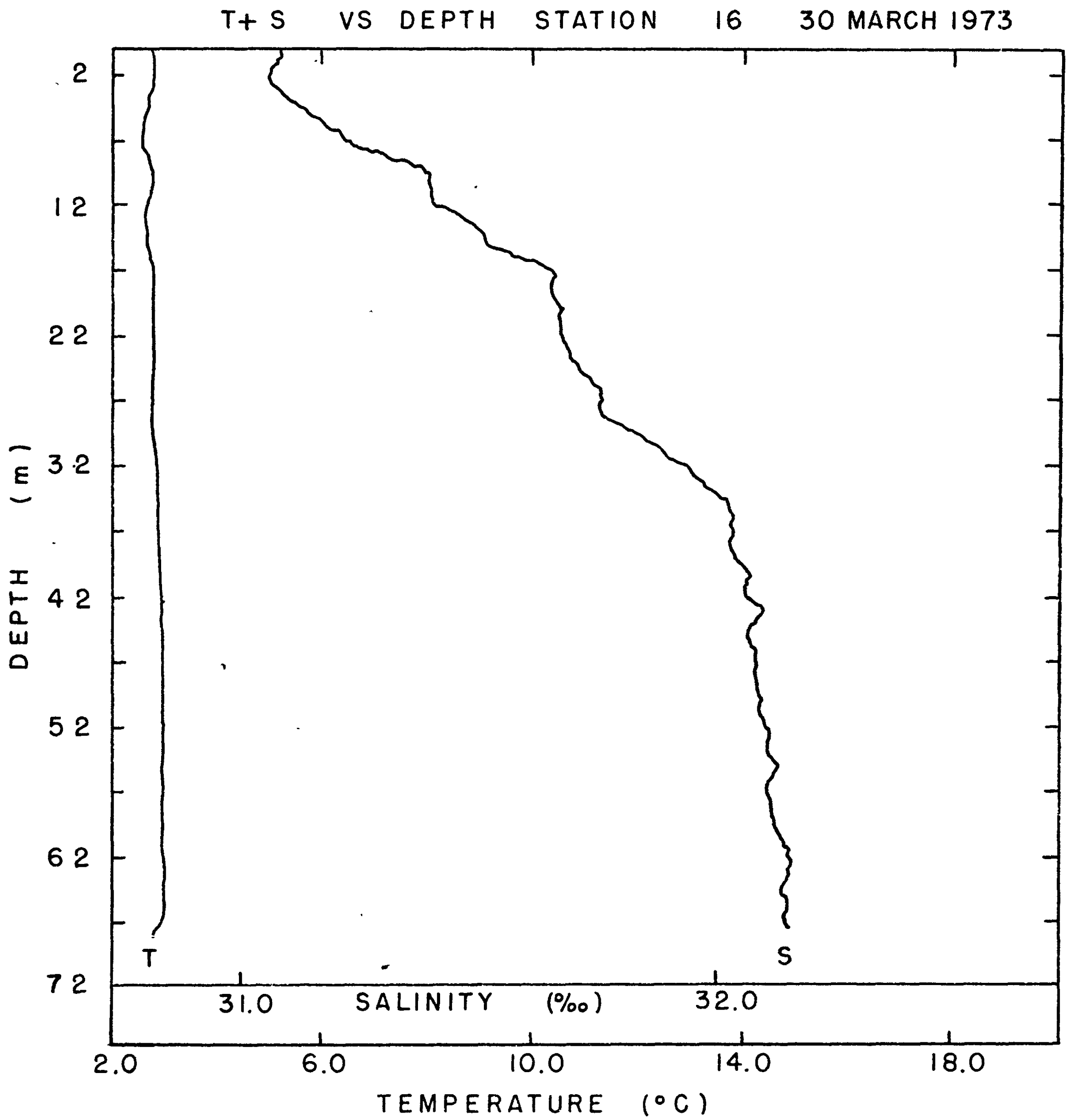


Figure 3: Salinity and Temperature vs Depth at Station 16, 29-30 March

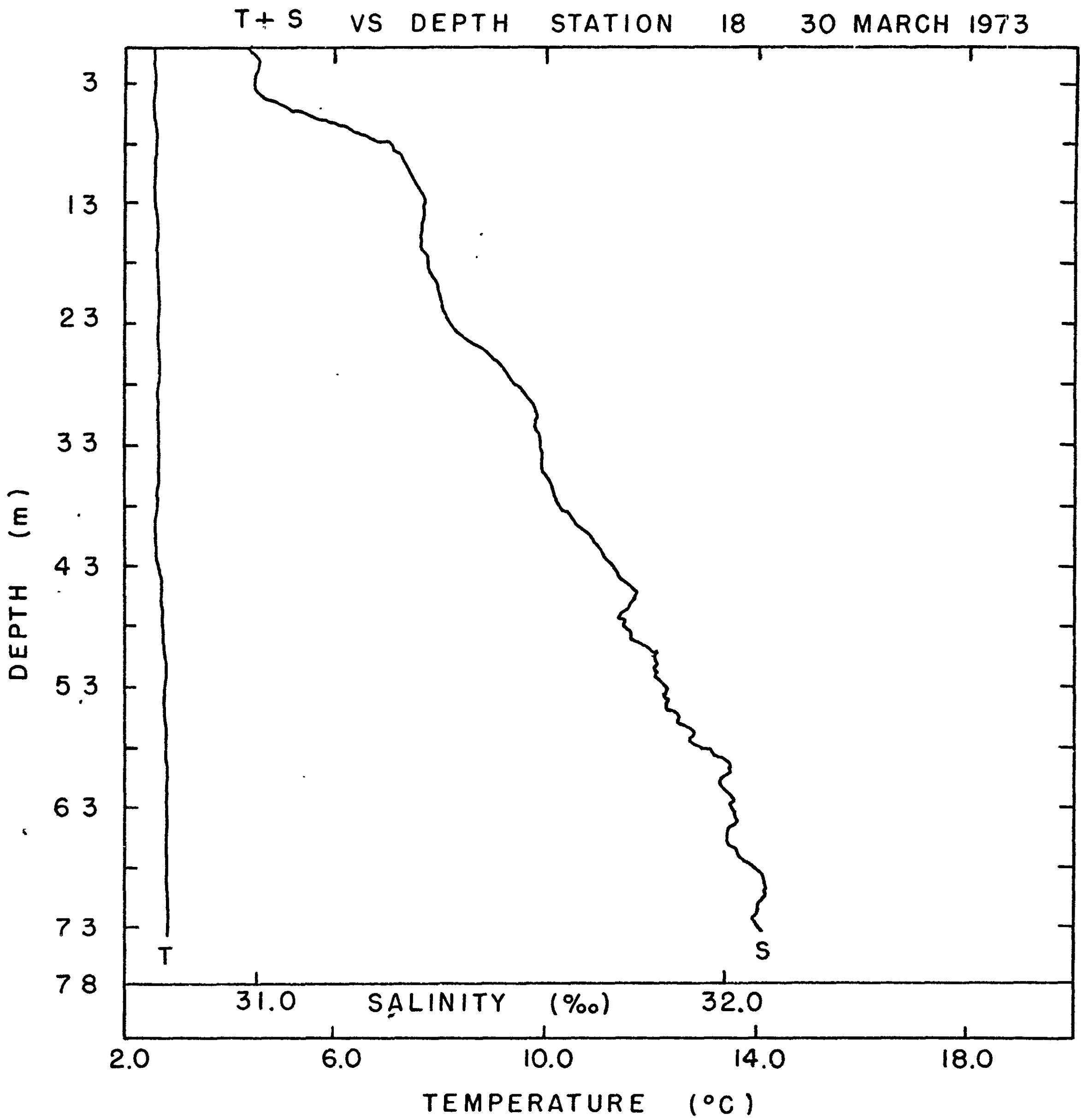


Figure 4: Salinity and Temperature vs Depth at Station 18, 29-30 March

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